Nova Analysis: Holistically Valuing the Contributions of Residential Efficiency, Solar and Storage

Jeff Maguire, Michael Blonsky, Sean Ericson, Amanda Farthing, Indu Manogaran, and Sugi Ramaraj

National Renewable Energy Laboratory

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Technical Report
NREL/TP-5500-84658
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

List of Acronyms

DER	distributed energy resources
EE	energy efficiency
EIA	U.S. Energy Information Administration
HVAC	heating, ventilating, and air conditioning
LRMER	long-run marginal emissions rate
NPV	net present value
NREL	National Renewable Energy Laboratory
OCHRE	Object-oriented Controllable High-resolution Residential Energy model
PV	photovoltaics
RA	resource adequacy

Executive Summary

Policies to address climate change and grid modernization, in combination with cost reductions and technological advancements in energy efficiency (EE) and distributed energy resources (DER), are driving rapid deployment of building electrification and energy efficiency retrofits, rooftop solar photovoltaics (PV), smart thermostats, smart water heaters, and battery energy storage. In residential buildings, the most common DERs are solar panels and battery storage. Utilities, grid operators, product providers, aggregators, and consumers want a more detailed understanding of the value of these resources, but the key metrics are different for each stakeholder and actions that may increase value to one stakeholder may decrease it for another, creating a complicated set of interactions when trying to holistically value buildings with these technologies.

EE and DER upgrades can lead to utility bill savings for the homeowner, provide utility benefits, and provide societal benefits such as a reduction in greenhouse gas emissions and other negative externalities. At the same time, these upgrades can be costly, and the benefits do not always outweigh the costs. Multiple stakeholders contribute to the decision of whether to invest in home energy upgrades. Homeowners determine which upgrades to purchase and have installed, or which new home to buy.. Builders determine the amount of EE to install in new buildings, and whether to integrate DER upgrades. Utilities and regulators set the rate structure and can offer incentives to support EE and DER adoption. Finally, the local, state, and federal government sets policy, determines building codes, and provides incentives for EE and DER.

A broad suite of performance metrics is required to provide a holistic picture of how EE and DER upgrades affect each stakeholder, and how their value varies by home. This report quantifies the relative and combined value of EE and DER investments within the residential, single-family home sector. The new workflow developed combines multiple tools from both the buildings and the solar plus storage domain to enable this analysis from the perspective of multiple stakeholders. This allows simulations to be performed for residential buildings to be modeled anywhere in the country with any efficiency features, pairing the building with the appropriate residential utility rate from the Utility Rate Database, and then allowing optimization of a solar plus system for the building. This approach allows for a much richer suite of metrics to be calculated than through analyzing EE and DERs separately.

Our workflow has the capability to model granular spatial diversity in utility rates, housing stock, and solar capacity across the United States. To demonstrate the applicability of this workflow, simulations were performed for a sample of 300 single family detached homes spread across the country. These homes were simulated under a variety of different conditions, with efficiency and electrification[1] upgrades for the homes and then with several combinations of DERs. Figure ES-1 shows the results from one of these scenarios, where no efficiency upgrades are applied but DERs.

[1] The "electrification" package used here applied higher efficiency equipment to all homes. For homes that already had space cooling, in many cases this was an upgrade to the cooling efficiency. A more detailed analysis of electrification of the entire residential housing stock in the U.S. is included in (Present, 2022).

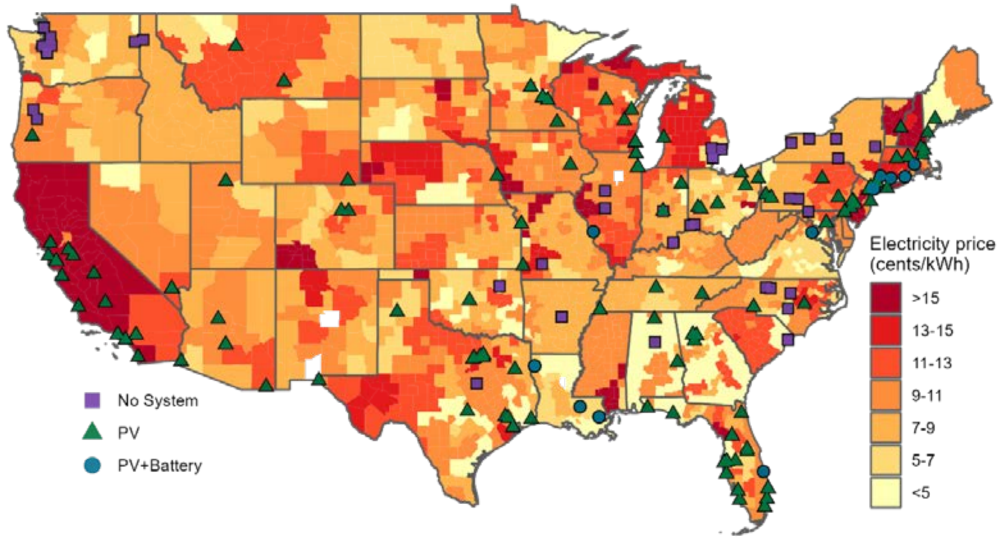

Figure ES-1. Location of homes with cost-effective DERs, overlaid with electricity price by county

Figure ES-2 displays the fuel and energy savings from the energy efficiency upgrades considered here across various climate zones. Our analysis at scale highlights similarities and differences across building types and climate regions, which provide insights into where energy efficiency and distributed energy resources are most likely to provide positive value.

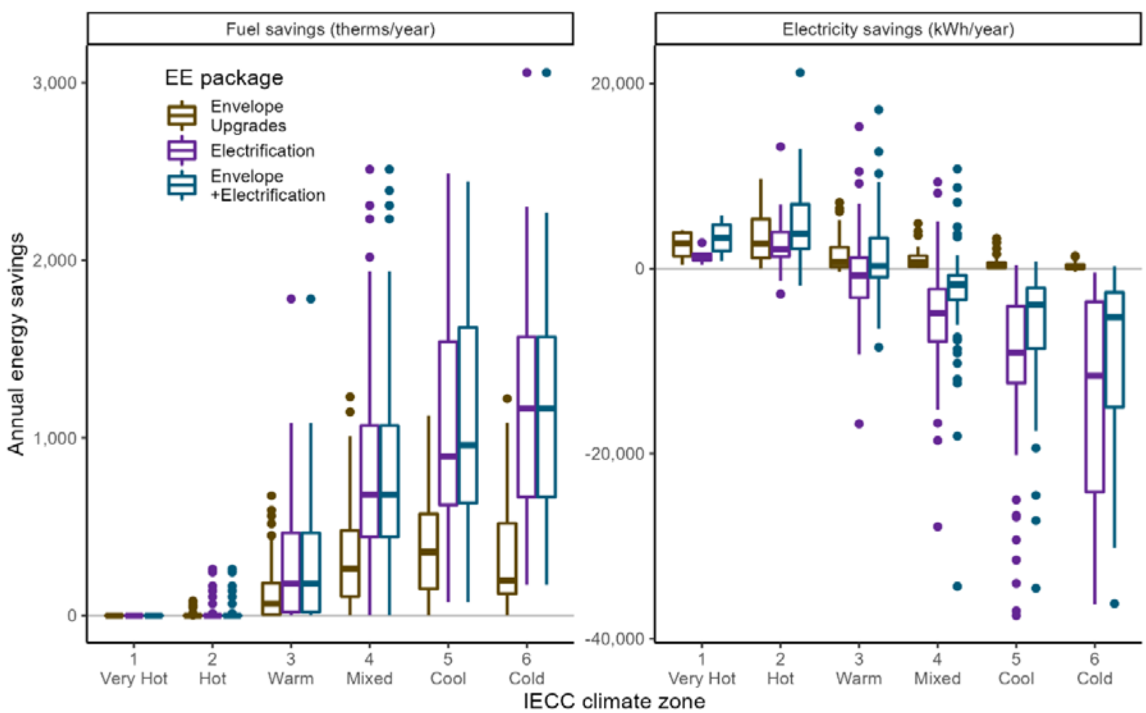

Figure ES-2. Annual energy use reduction for the three EE upgrades, by IECC climate zone

On top of the efficiency packages, we also modeled several different DER deployment scenarios, including a cost optimally (for the homeowner) sized system, situations without net metering, when resource adequacy is valued, if DERs became lower cost, and if a cost for emissions were passed onto the homeowner. Our results, along with the workflow developed to produce these results, provide metrics relevant to homeowners, utility and grid operators, and broader society. Figure ES-3 displays the annual carbon emissions reduction for energy efficiency and optimally sized PV and battery packages across scenarios, which is an important metric for considering the broader societal impacts of home energy upgrades.

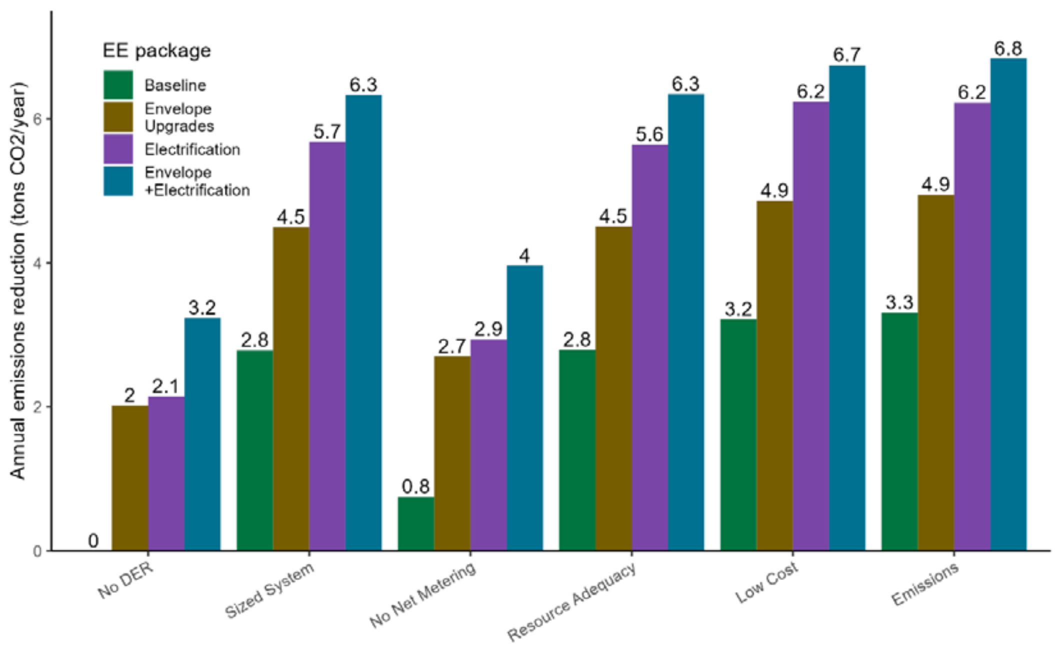

Figure ES-3. Annual emissions reduction by scenario and energy efficiency upgrade

Through our analysis, we find several results worth highlighting.

- The value for all metrics considered here of efficiency and electrification upgrades depend on the climate zone, the relative electricity and fuel costs and emissions rates, and the baseline heating fuel. Buildings using fuel oil tend to have the highest value of efficiency upgrades.

- Given our installed cost and utility rate assumptions, PV is cost-effective and battery systems are not cost-effective in most residential homes. The cost effectiveness of PV (in situations where the PV system is optimally sized for the homeowner) increases when installed costs are reduced or when emissions benefits can be monetized. Battery adoption increases when net metering is not allowed and when utility resource adequacy benefits can be monetized. Home envelope upgrades have negative synergies with PV, resulting in lower optimal PV sizes, while electrification has positive synergies with PV, resulting in larger optimal PV sizes.

- Combined energy efficiency and DER upgrades result in average emission reductions of 4.5–6.3 tons of CO_2 equivalent per year, roughly equivalent to taking a car off the road.

- While electrification upgrades on their own tend to increase wholesale electricity costs, they reduce wholesale electricity costs when coupled with DER upgrades. This is because electrification enables larger PV systems to become cost-effective. Added benefits of more PV outweigh the additional electricity use from electrification, leading to a net reduction in wholesale electricity costs.

- The electrification package considered here often reduces home loads during grid peak hours because heat pumps replace less efficient air conditioners that often contribute to the summer peak. However, this finding is dependent on the local climate and may not hold for locations where broad electrification may shift grid peaks from summer to winter months.

- We find small negative interactions between building envelope upgrades and electrification, suggesting that these upgrades provide slightly less reduction in utility bills than the simple sum of the benefits of each upgrade when they are combined. Envelope upgrades reduce the total heating and cooling load, which in turn reduces the savings potential of upgrades to the heating and cooling systems compared to cases without envelope upgrades.

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1 Introduction

In the United States, homes account for 20% of greenhouse gas emissions (Goldstein et al., 2020), 37% of total electricity consumption (Nalley & LaRose, 2022), and 15% of direct natural gas use (EIA, 2022b). Utility bills can also comprise a substantial portion of an occupant's budget. The average residential customer pays around $1,400 per year for electricity and $700 per year for gas, and these costs can be significantly higher depending on climate, utility prices, and building efficiency. An estimated 25% of U.S. households experience energy poverty (defined as spending more than 6% of household income on energy expenditures) and approximately 13% face severe energy poverty (defined as spending more than 10% of income on energy) (Drehobl et al., 2020; Scheier & Kittner, 2022).

Policies to address climate change and grid modernization, in combination with cost reductions and technological advancements in energy efficiency (EE) and distributed energy resources (DER), are driving rapid deployment of building electrification and energy efficiency retrofits, rooftop solar photovoltaics (PV), smart thermostats, smart water heaters, and battery energy storage. Utilities, grid operators, product providers, aggregators, and consumers want a more detailed understanding of the value of these resources.

EE and DER upgrades can lead to utility bill savings for the homeowner, provide utility benefits, and provide societal benefits such as a reduction in greenhouse gas emissions and other negative externalities. At the same time, these upgrades can be costly, and the benefits do not always outweigh the costs. The value of home energy investments depends on a variety of factors including home vintage and size, current home efficiency, electricity and fuel prices, and climate. Combining EE and DER investments further complicates the problem by producing both positive and negative interactions depending on the specific upgrades and building characteristics. The value of one upgrade depends on its interaction with other investments, so the combination of multiple DERs and EE investments presents a challenge with respect to assessing the value that they deliver.

Multiple stakeholders contribute to the decision of whether to invest in home energy upgrades. Homeowners determine which retrofits to purchase and have installed, or which new home to buy. Builders determine the amount of EE to install in new buildings, and whether to integrate DER upgrades. Utilities set the rate structure and can offer incentives to support EE and DER adoption. Finally, the local and federal government sets policy, determines building codes, and can provide incentives for EE and DER.

The value and performance of EE and DER upgrades have traditionally been measured with the metric of annual energy reduction, which also serves as a proxy for reductions in energy system costs and/or emissions. However, for many stakeholders, the metric of energy reduction does not capture many of the benefits of EE and DER upgrades most saliant to them. It also does not consider the spatial and temporal heterogeneity in electricity and emission rates, meaning that two upgrades with similar levels of energy reduction could have large differences in cost and emissions reductions. EE upgrades further affect both home fuel use and electricity use, which can have differing impacts on costs and emissions. A broader suite of performance metrics is required to provide an overall picture of how EE and DER upgrades affect each stakeholder, and how their value varies by home.

This report quantifies the relative and combined value of EE and DER investments within the residential single-family home sector. It is the final report of the two-year Nova Analysis project, headed by the National Renewable Energy Laboratory (NREL) with funding from the U.S. Department of Energy's Solar Energy Technologies Office. Through the Nova Analysis project, we developed a scalable analysis framework that evaluates residential EE and DER upgrades, including envelope upgrades, electrification upgrades, and PV and storage adoption, across a broad set of buildings and locations using a consistent set of metrics. The granular spatiotemporal approach developed through our analysis allows for a much richer suite of metrics to be calculated than through separate analysis of EE and DERs. We present results for 300 simulated buildings across the United States.

2 Methodology

We developed a scalable analysis framework that evaluates residential EE and DER upgrades, including envelope upgrades, electrification upgrades, and PV and storage adoption, across a broad set of buildings and locations using a consistent set of metrics. The framework uses a variety of NREL tools and publicly available datasets to ensure that the framework is applicable across the United States and does not require proprietary data. The metrics quantify the EE and DER upgrade value in terms of savings to the homeowner, impact on the grid, carbon emissions reduction, and other value streams. The modeling approach captures the effects of building type, climate, utility rate, and occupant preferences on upgrade value as well as the interactions between multiple upgrades, such as a combination of energy efficiency and DER adoption.

2.1 Metric Identification

We identified a set of metrics that capture the various value streams and stakeholder perspectives relevant to measuring the value of EE and DER upgrades. The process for reviewing, selecting, calculating, and reporting metrics is shown in Figure 1. The identification process included a broad literature review of existing metrics for related applications. Key metrics were selected based on their relevance to and importance for key stakeholder decision-making processes and on the ability to calculate them with available data across the United States. Relevant metrics were calculated through the case studies, and finally, the matrix of metrics relevant to stakeholder priorities was reported.

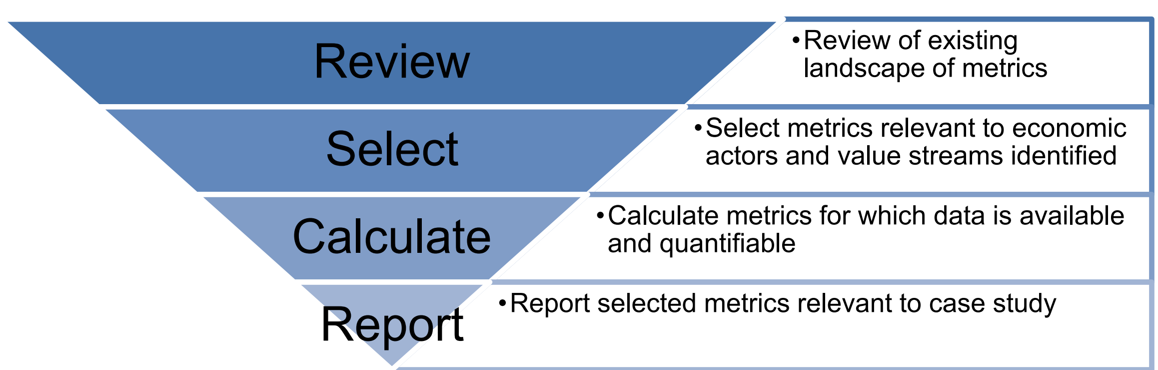

Figure 1. Process for selecting metrics to report

We updated a literature review conducted in previous work (Shah et al., 2020) to understand the existing landscape of metrics related to zero energy buildings, demand flexibility, bulk power reliability, resilience, value of DERs and other related topics. The literature review began with a broad lens, considering all power system actors and identifying the variety of needs or system requirements associated with these actors.

We selected metrics that are relevant to the key stakeholders involved in EE and DER upgrades. These stakeholders are the homeowner, utility, and society at large.[2] The homeowner is assumed to value their energy usage, the cost of energy and upgrades, energy resilience, and comfort. The utility encompasses the retail energy provider, distribution system operator, and wholesale energy provider, and is assumed to value the wholesale energy cost and peak demand contribution. The societal stakeholder is assumed to value the reduction of carbon and other emissions.

We filtered metrics based on their ability to be accurately calculated using publicly available datasets that span the United States. Some metrics were removed from the framework due to proprietary data requirements or uncertainty caused by a lack of data. In particular, this framework does not consider the value of EE and DER on the distribution system, including impacts on congestion, hosting capacity, or reliability. Distribution system architectures can vary considerably within and across regions, and there is limited data to quantify these value streams.

Some metrics, such as annual energy costs, are measured as absolute values while other metrics, such as annual energy cost reductions, are measured as changes compared to a relevant baseline. The baseline is most commonly the same home without an upgrade but can be a comparison to other homes with a Home Energy Rating System (HERS) or ENERGY STAR® score. If multiple upgrades are included, then multiple baselines can be calculated, with the appropriate baseline depending on the question of interest. For example, if both EE and DER upgrades are included, then energy savings from the DER can be calculated either before or after the EE upgrades are included.

There is not a single "best" metric, but instead there are a suite of metrics to consider, with the most appropriate metric depending on the interested stakeholder, whether there is a relevant baseline, the scope of analysis, and the amount of input data available. Table 1 lists and describes the metrics produced from our framework and indicates primary stakeholder along with whether the metric requires a baseline for comparison. We note that not all metrics are presented in this report's results, but all can be calculated using the analysis framework.

[2] Several of the metrics are important to multiple stakeholders. For example, values important to a home's occupant are also relevant to EE and DER providers, and utility and grid operators.

Table 1. Metrics included in this analysis framework

	Metric Name	Unit	Description	Requires Baseline
Homeowner Metrics	**Annual Energy Use**	kWh/year, therms/year	Calculated separately for electricity and fuel.	No
	Annual Energy Savings	kWh/year, therms/year	Change in annual energy use compared to baseline. Calculated separately for electricity and fuel.	Yes
	Annual Utility Bill	$/year	Sum of retail electricity and fuel costs.	No
	Annual Bill Savings	$/year	Change in annual utility bill compared to baseline.	Yes
	Life Cycle Cost (LCC)	$	Present value of energy bills, investment costs, and operation and maintenance costs over analysis period.[3]	No
	Net Present Value	$	Change in LCC compared to baseline.	Yes
	Outage Resilience	hours	Average hours building can sustain loads during an outage. Determined by averaging survivability time for an outage beginning in each hour of the year.	No
	Occupant Discomfort	°C-hours	For buildings with HVAC (or water heating) demand flexibility strategies, degree hours of unmet load.	No
	Cover Factor Demand	%	Percent of total home load covered by DER. Calculated as self-consumed DER generation divided by gross home load.	No
Utility Metrics	**Wholesale Electricity Cost**	$/year	Wholesale utility cost to serve a building's net load. It uses the hourly grid marginal cost of electricity.	No
	Wholesale Electricity Cost Savings	$/year	Change in annual wholesale electricity cost compared to the baseline.	Yes
	Grid Peak Contribution	%	The degree to which a building load peaks during the top 5% of bulk power system peak hours as defined in Cambium. Calculated as the ratio of the building's net load during the top 5% peak grid hours to its	No

[3] Life cycle cost and net present value are only calculated for DER upgrades, not for EE upgrades. This is due to a lack of data for costs and expected lifetimes for EE upgrades across the United States.

			net load during the building's 10 highest peak hours.	
	Peak Load Reduction	kW	Load reduction of an upgrade at grid peak hour.	Yes
	Resource Adequacy (RA) Cost Savings	$/year	Change in utility RA costs compared to baseline. It is a product of the savings load profile and the utility cost of capacity.[4]	Yes
Societal Metrics	**Annual Emissions**	tons/year (CO_2 equivalent[5]), lbs/year (SO_2, NOx)	Sum of emissions from home fuel use and net electricity use. Grid emissions use a long-run marginal emissions rate. Separate calculations for CO_2e, SO_2 and NOx.	No
	Annual Emissions Reduction	tons/year (CO_2e), lbs/year (SO_2, NOx)	Change in annual emissions compared to the baseline.	Yes
	Value of Annual Emissions Reduction	$/year	Present value of emission reductions from upgrade. CO_2e emission reduction value reported separately from SO_2 and NOx. Social cost of carbon set at $51/ton (White House, 2023).	Yes

[4] Resource adequacy targets ensure that a utility has sufficient reliable capacity to meet demand over time. GEB's can contribute to resource adequacy by reducing demand during peak load hours. In this study, we opt to determine the "true" resource adequacy potential and associated capacity value. To this end, we use Cambium's hourly marginal capacity cost values as described in Section 2.3.

[5] CO_2 equivalent is the CO_2 emissions with the same global warming potential as the total emissions from greenhouse gasses. All references to CO_2e in this report are to CO_2 equivalent.

2.2 Input Datasets

The metric calculations described above require data on energy costs, grid impacts, and emissions impacts of EE and DER upgrades. The workflow is designed to model homes with EE and DER upgrades anywhere in the contiguous United States without the need for proprietary data. As such, all input datasets used are public and span the contiguous United States. The following datasets are incorporated into the metrics calculations:

- The Utility Rate Database provides rate structure information from most utilities in the United States (DOE, 2022). The database includes rates from nearly 4,000 utilities. The rate structures include information on tiered rates, time-of-use rates, demand charges, and other rate options. This project used the Utility Rate Database to determine a default residential rate for each county in the contiguous United States, which was then used to calculate electricity costs. Figure 2 displays average electricity prices for the default utility rate used by county. The black points denote the location of homes in the study. While average prices are shown here, all bill calculations were done using the actual rate structure to account for things like tiered and time-of-use rates.

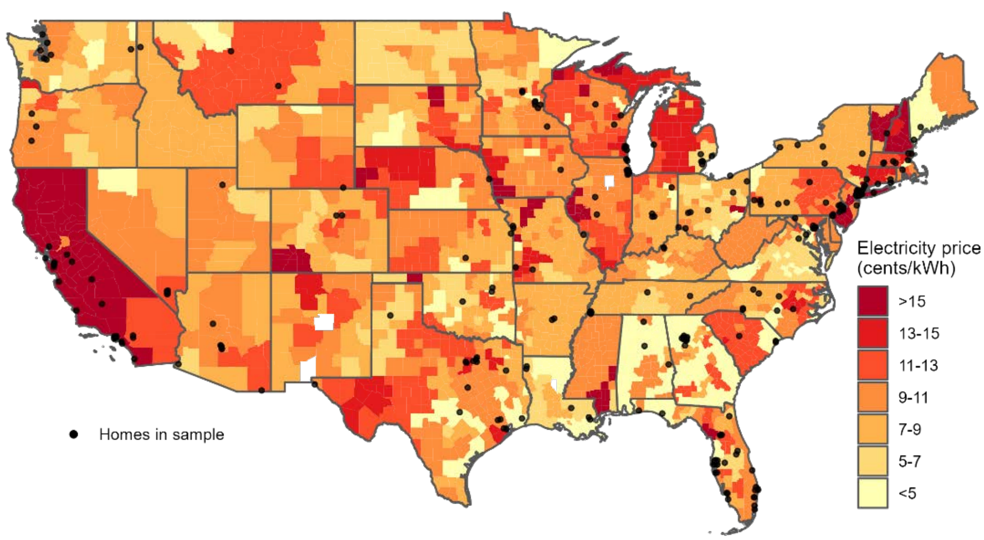

Figure 2. Map of electricity price by county for the default utility rate. For multi-tiered rates, the price shown is based on the first tier and for time-of-use rates the off peak rate is shown. Points denote the location of homes in this study. Rates from the National Utility Rate Database.

- Cambium is an NREL analysis tool that reports cost, emissions, and operational data for modeled scenarios of the U.S. electricity grid at multiple time and geographic resolutions (Gagnon et al., 2021). The results in this report used hourly data from the 2021 Mid-Case scenario for the year 2022 using a state-level geographic resolution. Since Cambium is based on projecting out into the future, there are multiple scenarios with different emissions factors that could be used. The 2021 Mid-Case scenario may be slightly conservative as the impacts of the Inflation Reduction Act, which hadn't yet passed, are not included. Three Cambium variables were used in this framework:

- **Emission rates:** We use Cambium's "Long-Run Marginal Emissions Rates" (LRMERs) to quantify carbon dioxide-equivalent emissions reductions. These rates are levelized across 25 years to account for changes in the generation mix across the lifetime of an upgrade (see Appendix for more details). They are also used in the Emissions Cost DER optimization scenario, which incorporates emissions costs in the optimal sizing and dispatch strategy of the DERs in REopt®.
- **Cost of capacity:** We use Cambium's "End Use Marginal Cost of Capacity" to calculate the potential benefits of reducing demand during peak hours on utility resource adequacy costs. Cambium's marginal cost of capacity is non-zero for approximately 100 hours of the year with the largest capacity constraints due to peak load or transmission congestion. By using this cost in our analysis, we effectively incorporate the value of utility resource adequacy into the value stack of the EE or DER upgrade. The marginal cost of capacity is used to calculate the Resource Adequacy Cost metric. It is also used in the Resource Adequacy DER optimization scenario, which incorporates this cost in the REopt optimization.
- **Hourly wholesale electricity costs:** We use Cambium's "End Use Marginal Cost of Electricity" to quantify the annual wholesale electricity cost to meet home loads. This denotes the hourly cost to produce and transmit wholesale electricity.

- The U.S. Energy Information Administration's (EIA's) natural gas, fuel oil, and propane costs were used to calculate the energy costs for these fuels (EIA, 2022a). Monthly fuel costs[6] by state were combined with Object-oriented Controllable High-resolution Residential Energy model (OCHRE™) outputs of hourly home gas usage to calculate the annual fuel cost of the home. This was incorporated into the NPV metric for electrification upgrades, as these upgrades impact the household costs for both electricity and fuel.

2.3 Overall Workflow

The analysis framework is designed to evaluate EE and DER upgrades across a broad set of buildings and locations using a consistent set of metrics. The modeling tools and input sources described above are integrated into a single analysis workflow. NREL tools are used to create residential building models, add energy upgrades, and optimize the size and control strategies of DERs. The workflow entails the following steps, as outlined in Figure 3 and detailed below.

[6] Monthly fuel costs were calculated as the average residential fuel price for 2016–2021.

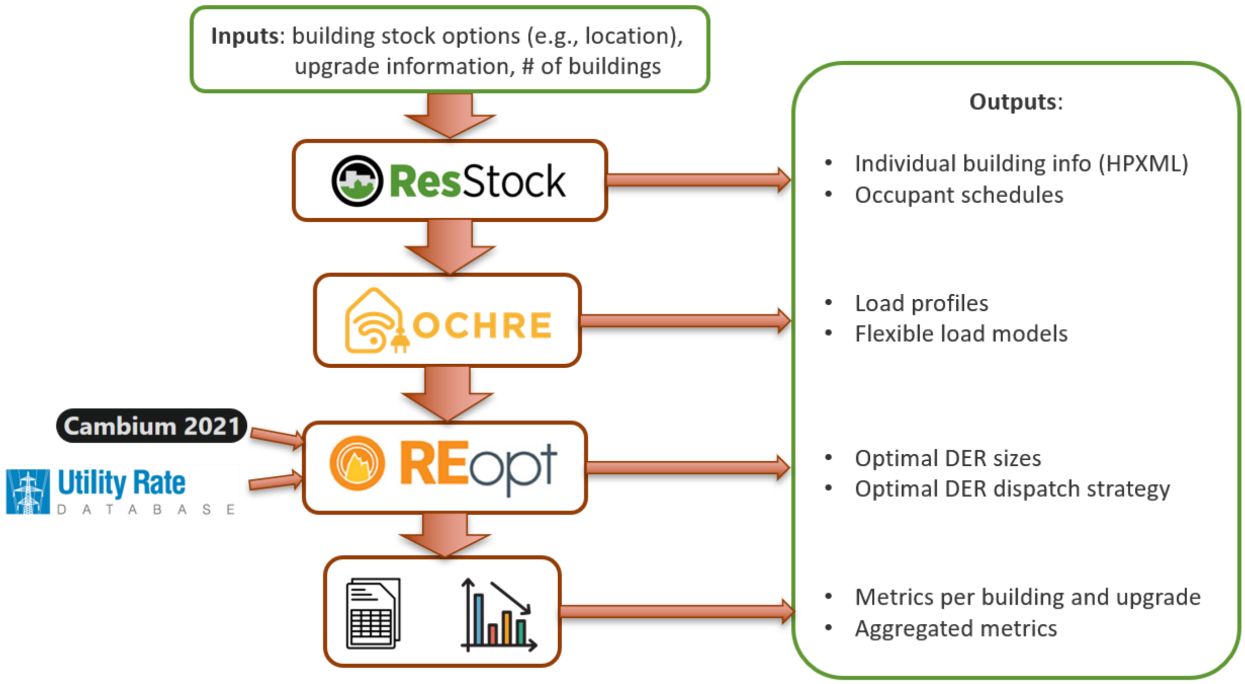

Figure 3. Visual representation of analysis workflow

1. Generate a list of building stock options and a set of EE and DER upgrades.

The Nova analysis workflow allows for the specification of a variety of inputs that determine the size and scope of the analysis. Key inputs include:

- Number of buildings to simulate
- Building characteristics (region of interest, type of buildings, vacancy status, etc.)
- Energy efficiency upgrade package options
- DER upgrade package options
- Specific scenarios
- Relevant baselines to calculate comparison metrics.

2. Run ResStock to generate a set of building models for a defined geographic scope.

ResStock™ is an analysis tool that creates a set of representative house models of the U.S. housing stock (Reyna et al., 2022; Wilson, 2017). It includes probability distributions for a variety of features that affect building energy consumption, including house size, insulation, energy-consuming equipment, equipment size and efficiency, and occupancy. The distributions include appropriate dependencies based on geographic location and other factors. ResStock can generate a set of models that represent the existing housing stock. It can also apply energy efficiency upgrades to the building models, for example envelope upgrades, or efficiency upgrades to heating, ventilating, and air conditioning (HVAC) equipment or water heaters.

ResStock is used to generate models of the home for both the baseline and any energy efficiency upgrades.. It creates a set of building models using the Home Performance XML (HPXML) data standard, which defines properties for each building's envelope, energy-consuming equipment, occupancy, and other information. ResStock also creates a stochastic occupancy schedule for each building that represents the energy-consuming behavior of the occupants. In this analysis, 300 homes were simulated distributed across the entire United States.

3. **Run OCHRE for each combination of building and EE upgrades to simulate the building energy consumption and generate flexible load models.**

OCHRE is a residential energy model that simulates energy consumption and occupant comfort for buildings with DERs and flexible loads (Blonsky et al., 2021). It includes controllable DER models for HVAC equipment, water heaters, electric vehicles, PV, and batteries. OCHRE is designed to be used in co-simulation with DER controllers and grid models or as an underlying model for energy control and optimization applications.

OCHRE uses the HPXML and occupancy schedule data to simulate each building model for one year. The models are simulated at 1-hour resolution. OCHRE determines the load profiles for electric and fuel end uses, which are used to calculate many of the metrics. OCHRE also creates simplified models for the HVAC and water heating systems that capture the dynamics of load shedding or load shifting on occupant comfort.

4. **Run REopt for each combination of building, EE upgrade, and DER optimization scenario to determine the optimal DER sizes and dispatch schedules.**

REopt is an optimization model that determines the cost-optimal deployment of distributed energy technologies while adhering to operational constraints (Cutler et al., 2017). The model identifies the system sizes and dispatch strategies that minimize the life cycle cost of energy, which can include customer costs, wholesale electricity costs, carbon emissions, and public health impacts over the financial life of a project.

REopt uses load profiles, flexible load models, and other information from OCHRE to optimize DER sizing and dispatch for multiple scenarios. Scenario parameters, such as what costs are used in the objective function, are integrated to adjust the REopt model's objective function, operating constraints, and the set of controlled DERs. In full flexibility cases, REopt optimizes the size of the PV and battery as well as the dispatch of the battery, electric HVAC equipment, and water heater.

5. **Calculate metrics from inputs and outputs from ResStock, OCHRE, and REopt.**

Data from ResStock, OCHRE, REopt, Cambium, and the Utility Rate Database are aggregated to calculate the desired metrics. Absolute metrics are calculated for each building and each scenario. Comparison metrics are calculated for some scenarios using a variety of baseline approaches. For example, a scenario with EE and DER upgrades can be compared to a baseline with no upgrades, EE only, or DER only. This approach allows metrics calculations to show the interactive effects of an upgrade on another upgrade's value.

2.4 Scenarios Analyzed

This study applies the analysis workflow described above to a set of buildings across the contiguous United States. The workflow was run for 300 buildings, each with a baseline and 3 energy efficiency upgrade packages, and 7 DER optimization scenarios. Building models only include single-family detached homes that are occupied (i.e., not vacant).

Upgrade packages were determined through extensive discussions with the NREL ResStock team. The team helped identify what level of upgrade is likely to be feasible in a retrofit scenario, appropriate costs as a retrofit measure, and how best to apply them nationally. Retrofit costs are used for calculating certain financial metrics such as net present value. We modeled two building upgrade packages, an envelope upgrade and an "electrification" package, along with a third scenario that considers both envelope and electrification upgrades as shown in Table 2.

The envelope upgrade packages matches the "basic envelope upgrade" package used in the End Use Savings Shape project, which performed large scale national runs of different energy efficiency upgrades in ResStock to generate load profiles for the entire housing stock under several upgrade scenarios (Present, 2022). Ceiling insulation was added based on climate zone. Highly leaky homes, with infiltration greater than 15 ACH_{50}, were air sealed to reduce infiltration by 30%. Uninsulated walls got "drill and fill" insulation, increasing the R value to R-13. Ducts were also sealed to 10% leakage and insulated to R-8.[7]

The electrification package upgrades homes with high-efficiency heat pumps for both space and water heating. Note that this is not technically full electrification as cooking and any other gas end uses were not electrified, but it does affect the majority of gas use in homes. For water heating, the models use a heat pump water heater with a rated uniform energy factor (UEF) of 3.3–3.5. The exact size and efficiency of the heat pump water heater depends on the size of the original water heater, which itself was sized based on the number of occupants. Homes with <4 occupants got a 50-gallon tank, those with 4–6 occupants got a 66-gallon tank, and homes with 7 or more occupants got an 80-gallon tank. For space heating and cooling, homes were upgraded with either a central air source heat pump or a ductless heat pump depending on whether the existing HVAC system had ducts. Ducted systems generally provide more even space conditioning and less comfort concerns, but it is cost prohibitive to install a ducting system as a retrofit if none already exists. If ducts were present in the building and it didn't already have a heat pump, a central unit with a rated efficiency of SEER 22/HSPF 10 was installed. Buildings without ducts got a mini-split heat pump with a rated efficiency of SEER 14.5/HSPF 8.2. Note that this means that homes without ducts use equipment with a lower nominal efficiency. This was based on the thinking of (Present, 2022) at the time. In all cases, equipment is sized to meet ACCA Manual J and Manual S load calculations (Rutkowski, 2011) for the larger of the two loads (heating or cooling).

[7] The envelope upgrades used here are further described on slide 17 of (Present, 2022), and the HVAC and water heating (electrification) upgrades are described on slide 22 and 30.

Table 2. Energy efficiency upgrade packages analyzed in this report

EE Upgrade Package	Add Insulation	Reduce Infiltration	Add Heat Pump Water Heater	Add Air Source or Mini-split Heat Pump
Baseline (No EE)				
Envelope Upgrade	X	X		
Electrification Upgrade			X	X
Envelope + Electrification Upgrade	X	X	X	X

DER optimization scenarios vary the set of DERs to control and the objective function used in the optimization. The default objective function considers the installation cost of DERs and the retail cost of electricity to the homeowner. Changes to this objective include resource adequacy costs, emissions costs, and adjustments to the retail rate by removing net metering. Table 3 describes the DER optimization scenarios considered in this study.

Table 3. DER optimization scenarios analyzed in this report. "Retail" denotes costs from utility retail rates. "Exports" denotes credits from exporting to the grid in net metering scenarios. "DER" denotes installation costs (and O&M and replacement costs — not shown in the table) for the PV and battery system RA Credits denote payments for reducing load during peak hours. CO_2e denotes the social cost of carbon emissions.

Optimization Scenario	Objective Costs	DER Costs
No DERs	None[8]	
Fixed Sized DERs	Retail – Exports + DER	\$2,300/kW PV + \$600/kW, \$300/kWh Battery
Resource Adequacy	Retail – Exports – RA Credits + DER	\$2,300/kW PV + \$600/kW, \$300/kWh Battery
No Net Metering	Retail + DER	\$2,300/kW PV + \$600/kW, \$300/kWh Battery
Low DER Costs	Retail – Exports + DER	\$1,600/kW PV + \$420/kW, \$210/kWh Battery
Emissions Costs	Retail – Exports + CO_2e[9] + DER	\$2,300/kW PV + \$600/kW, \$300/kWh Battery

2.5 Baseline Housing Stock Characteristics

We modeled 300 unique buildings for most of the scenarios, with the number of homes modeled picked primarily due to computational and time constraints. National scale ResStock runs typical

[8] "No DER" is a baseline scenario.
[9] Based on 2021 Cambium LRMER.

features over 500,000 unique building models, meaning the sample used here is not necessarily a nationally representative sample. While not a truly representative sample due to the computational costs associated with this workflow, which are much more intensive than a typical ResStock run, the sampling approach here will represent the housing stock as well as possible given the sample size constraints. Future studies could easily increase the number of buildings to capture a larger portion of this housing sector. Additional runs with a larger number of samples would give greater confidence in the conclusions drawn from this study and get closer to a truly representative sample.

To generate the building models, ResStock was sampled nationally to get the 300 most "typical" single-family detached homes. The ResStock sampling algorithm accounts for relative population density, so the majority of these homes are located in urban areas. A map of the home locations overlaid with the IECC climate zones in shown in Figure 4, and a count of houses by climate zone is shown in Figure 5.

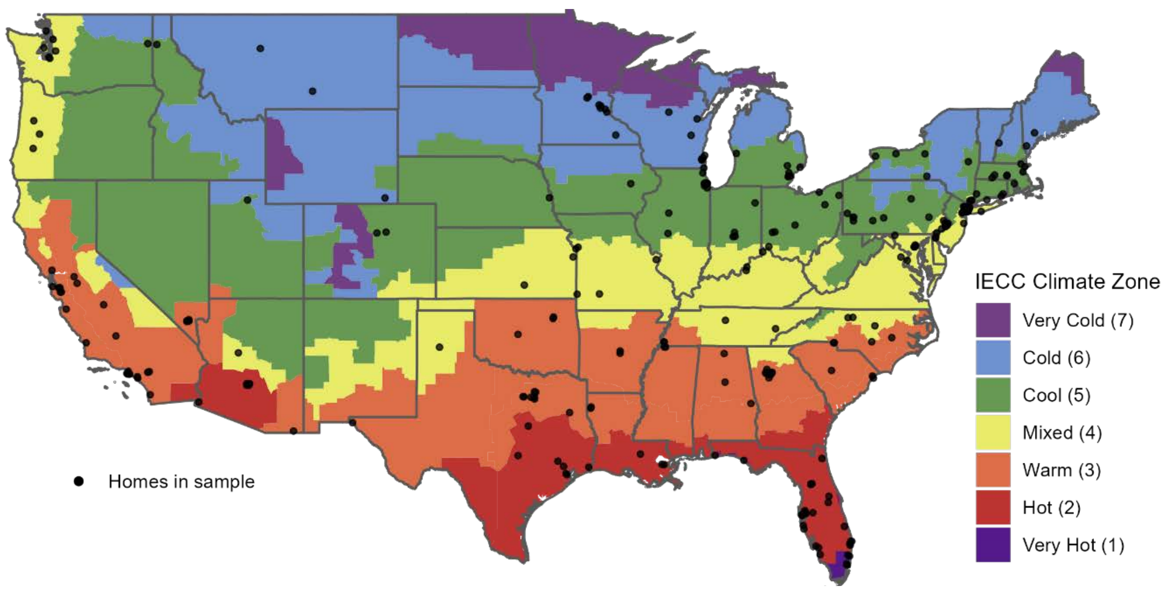

Figure 4. Location of sampled homes and IECC climate zones

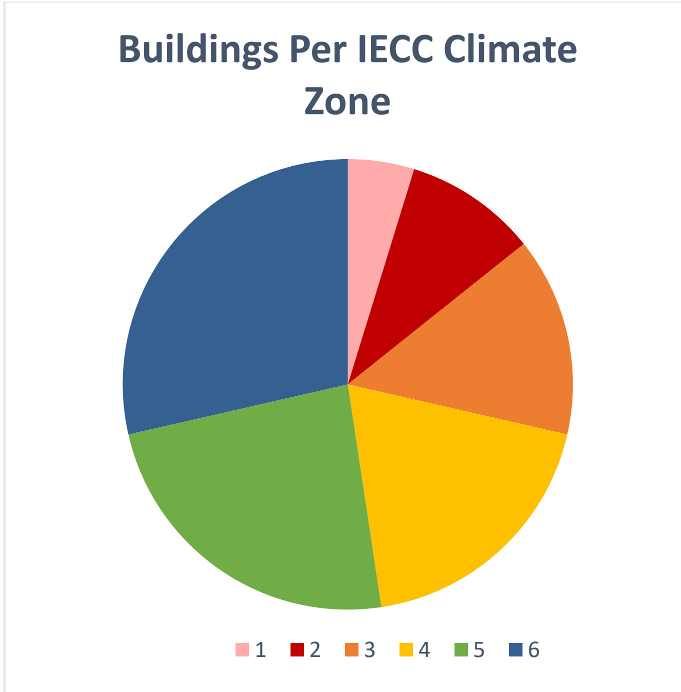

Figure 5. Fraction of homes in each climate zone

Figure 6 shows the distribution of vintage, heating fuel, water heating fuel, cooling type, floor area, foundation type, ceiling insulation, infiltration, and wall insulation in the baseline housing stock used in this study. Vintage is a useful proxy for the overall building efficiency. Older buildings tend to have less insulation, more leakage, and less efficient equipment. At a national scale, about half of the buildings were built before the 1950s. About 43% of the country uses natural gas for both space and water heating, although there is substantial regional variability. Electricity is generally used for space and water heating in the southeastern United States (because of a lack of natural gas infrastructure) and the Pacific Northwest (because of plentiful hydropower and cheap electricity prices) (Energy Information Agency, 2009). Rural locations are also less likely to use natural gas because of a lack of gas infrastructure. While most homeowners nationally with access to natural gas use it for both space and water heating, a substantial subset use natural gas only for space heating and electricity for water heating. Fuel oil makes up a small but non-negligible portion of the national housing stock, which is primarily concentrated in New England and the Mid-Atlantic region.

Central air conditioners are the most commonly used space cooling type, in approximately 50% of the housing stock, while room air conditioners are used in approximately 25% of the housing stock. The remaining space cooling is provided by air source heat pumps, used for both space heating and cooling. Approximately 16% of the housing stock has no cooling equipment. These buildings are primarily in cold locations with minimal cooling loads and are likely to be older homes. All homes have water and space heating, but not all have air conditioning. About 77% of the baseline houses have a floor area less than 2,500 sq. ft. Smaller homes are easier to maintain and consume less energy to power, heat, and cool, lowering the carbon footprint.

The difference in foundation is mostly dependent on climate. Basements are the most common type of foundation in colder climates, in about 36% of the housing stock. In warmer regions, homes are built on slabs, accounting for 39% of the building stock. Crawlspaces are commonly found in warmer and mixed climate regions. Infiltration is the largest contributing component to heating loads in all climate regions and can vary significantly based on house construction style, age, and region (Reyna et al., 2022). About 84% of the homes in this sample are "leaky" and have an ACH_{50} above 10.0. For ceiling insulation, R-30 is significantly more efficient and commonly used, accounting for 29% of the sample used here, while R-38 accounts for 21% of the sample. R-19 insulation is suitable for floors/ceilings in most homes and accounts for 23% of ceiling insulation. Wood stud is the most common wall type and accounts for 79% of the walls in this sample.

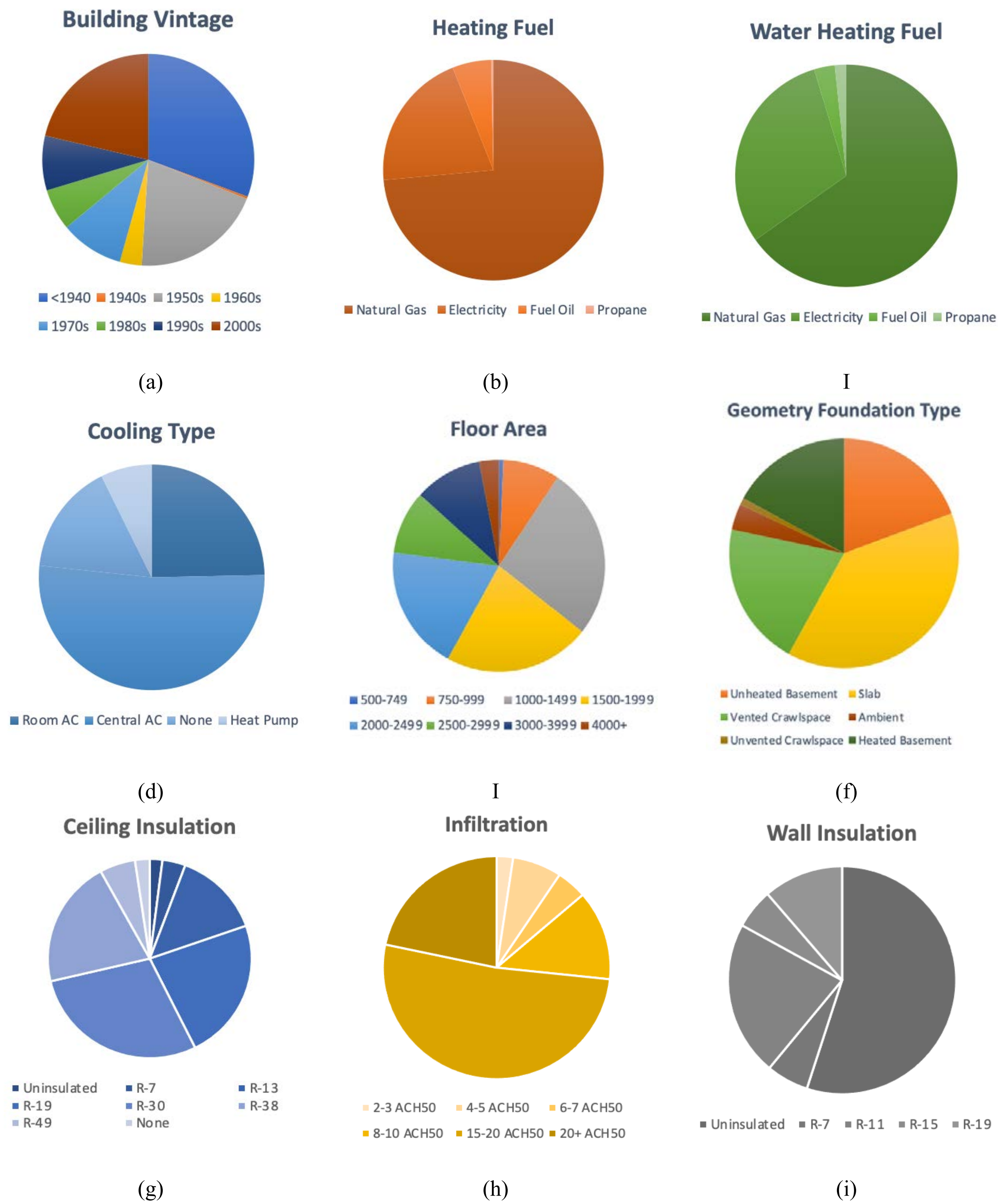

Figure 6(a-i). Vintage, heating fuel, water heating fuel, cooling type, floor area, foundation type, ceiling insulation, infiltration, and wall insulation in baseline buildings used in this study

3 Results

This section covers results for the various scenarios described in Section 2.5 that were simulated to demonstrate the full Nova Analysis workflow. We first show building baselines to give readers an understanding of the housing stock sampled. We next present results for building EE upgrades, then present results for DER sizing, and finally present results on the interaction between EE and DER upgrade scenarios. We highlight the most interesting changes in metric values associated with each upgrade to provide an understanding of how different factors impact the metrics and the key drivers of EE and DER upgrades.

3.1 Baseline Results

The baseline results show metrics of the existing housing stock as sampled from ResStock. The value of EE and DER upgrades depend on these baseline values for home energy use, energy costs, and emissions.

Figure 7 shows a box plot of the annual energy consumption by fuel and IECC climate zone. The geospatial nature of home loads, along with the importance of heating and cooling on total home energy use, is apparent. Fuel use for heating increases in colder climates due to higher heating requirements, primarily for space heating but also for water heating due to colder inlet water temperatures. Colder climates also have more homes that use fuel for heating. Electricity use for air conditioning increases in hotter climates due to higher cooling requirements. The prevalence of space cooling equipment is lower in cooler climates, particularly in older homes, and the prevalence of electrical resistance space and water heating is higher in warmer climates, further driving differences in home energy use by region.

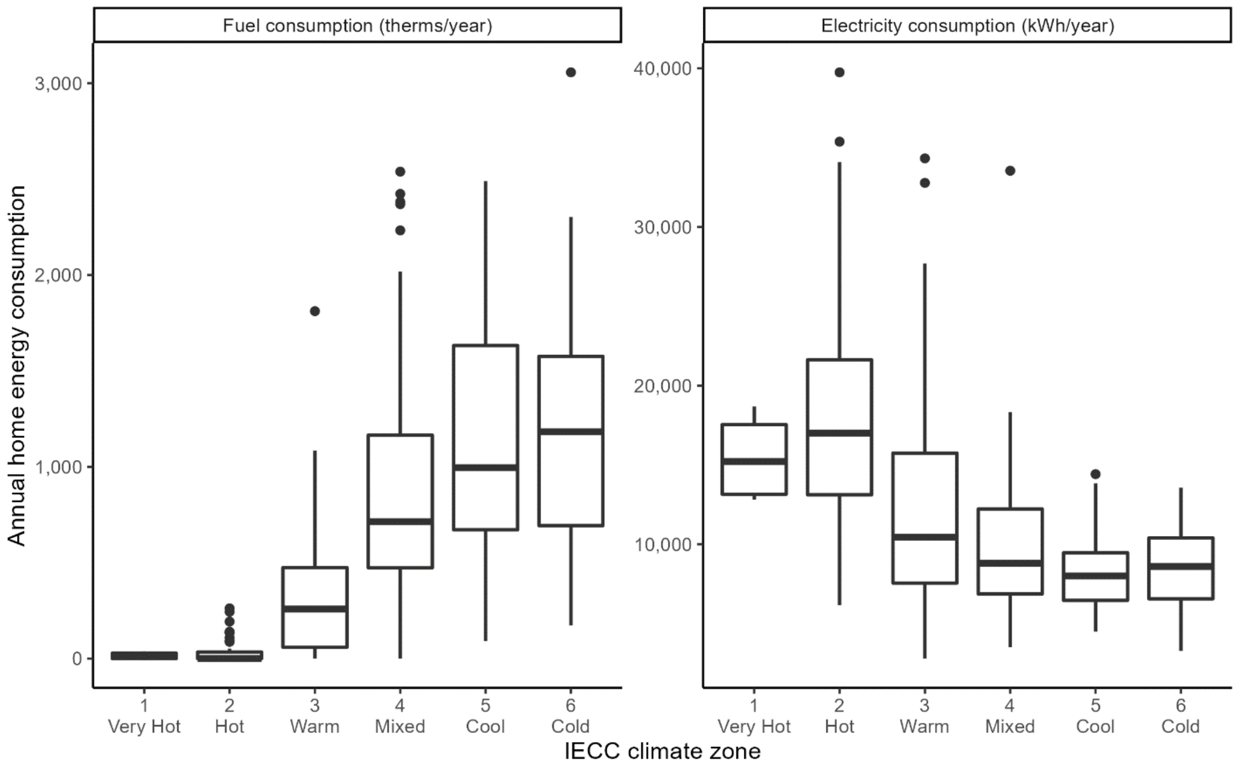

Figure 7. Annual total energy consumption by energy source and climate zone for baseline housing stock in this study

Figure 8 shows that total utility costs are relatively constant across climate regions while fuel and electric bills vary substantially with climate. Warmer climates tend to have lower annual fuel costs because of lower heating requirements and fuel availability, but also tend to have higher electricity bills because of higher cooling requirements and electricity use for space and water heating. The reverse is true of colder climates. While average annual utility bills are largely consistent across climate zones, there is large variation in utility bills across homes. These differences are driven by factors such as home size, equipment efficiency, and occupant behavior. As seen in Figure 2, residential electric rates vary significantly across utility regions, driving additional variation in utility bills. Fuel costs vary by the type of fuel used and by region; natural gas is generally less expensive than alternatives such as fuel oil or propane.

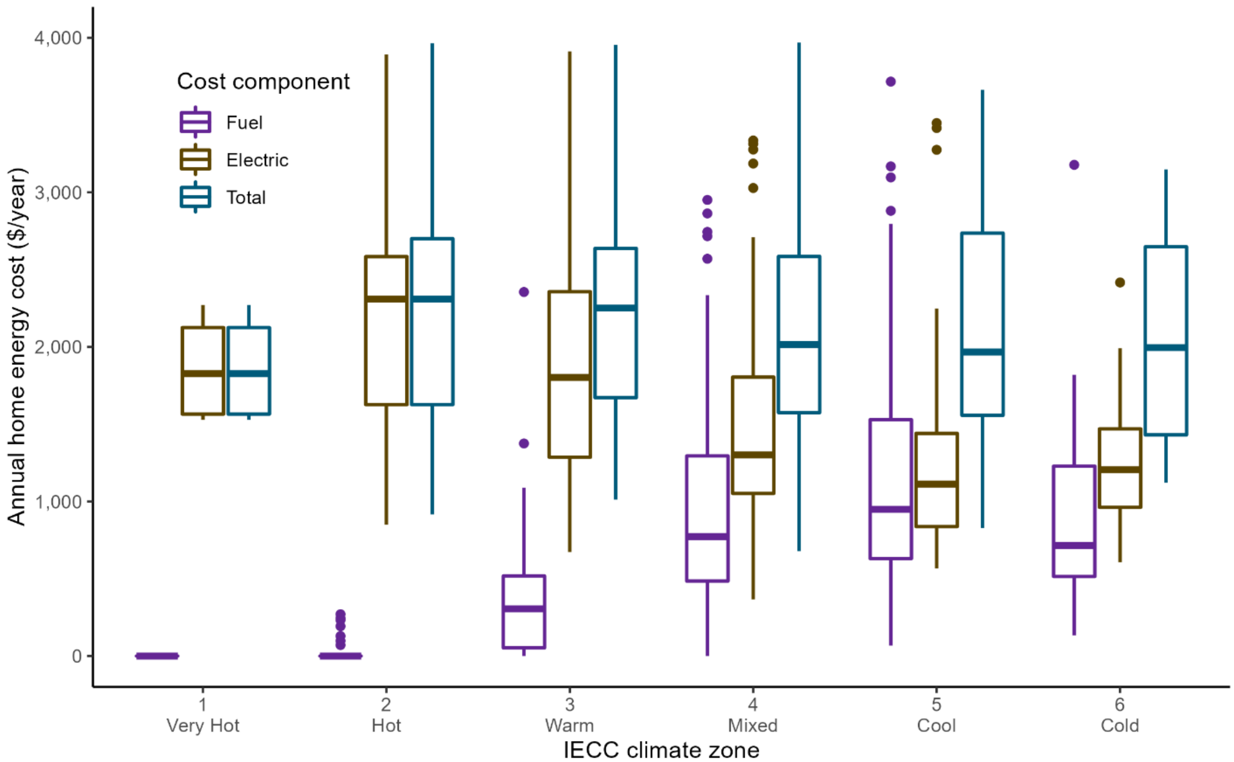

Figure 8. Annual utility bills by IECC climate zone for baseline housing stock

Annual home emissions are the sum of CO_2e emissions from grid-purchased electricity and from fuel use. We calculate fuel use emissions by multiplying total fuel use with a corresponding CO_2e emissions factor: 11.69 pounds per therm for natural gas and 16.31 pounds per therm for fuel oil (Anderson et al., n.d.).[10] We calculate grid electricity emissions by multiplying the home's hourly net load by hourly levelized long-run marginal grid emissions rates for the given location as described in Appendix A.1 of the REopt User Manual (Anderson et al., n.d.). This levelized rate accounts for projected changes in grid emissions over the assumed 25-year project lifetimes. Future year benefits are discounted using an 8.3% discount rate (Anderson et al., n.d.).

Marginal emissions rates are most appropriate to quantify how the grid will respond to a change in load, whereas average emissions rates are typically more appropriate for determining the emissions footprint of existing operations (Ryan et al., 2016). We present both baseline (total) and emissions savings results using long-run marginal, rather than average, emissions rates because we are primarily interested in quantifying avoided emissions from an intervention. Using the same rate type for savings and total emissions allows for a comparison of relative value of savings to total emissions. We note that marginal emissions rates are typically higher than average emissions rates.

[10] The values used here are consistent with typical REopt based analyses, but may not be consistent with other ResStock analyses. Any attempts to compare results here to other ResStock runs will include this and other differences.

Figure 9 displays annual home emissions by climate region and by emissions source. Total emissions are largely consistent across climates, though the composition of emissions sources varies. Homes in warmer regions tend to have lower fuel emissions and higher grid emissions. Thus, increasing the fraction of generation from zero emission sources in warmer regions will have a larger impact on home emissions than a similar increase in colder regions. Similarly, increasing building heating efficiency in colder regions will have a larger climate impact.

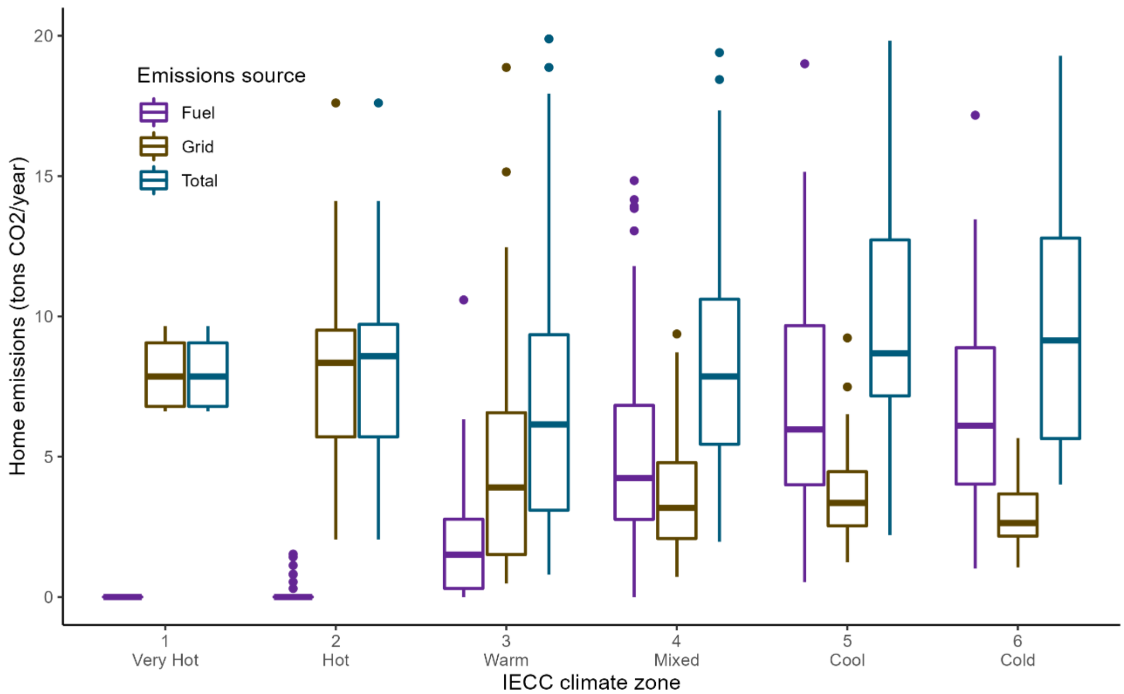

Figure 9. Annual home emissions by IECC climate zone for baseline housing stock used in this study

3.2 Impacts of Efficiency Measures

As discussed in Section 2.5, three different energy efficiency scenarios were simulated: an envelope upgrade package, an efficient electrification package, and a combined package of both upgrades. Figure 10 shows the annual fuel and electricity reductions from the EE upgrade scenarios.

The envelope upgrade decreases both fuel and electricity use, with the reduction in fuel use highest in colder regions. The electrification package converts space heating to an electric air source heat pump and installs a heat pump water heater, nearly eliminating home fuel use,[11] and increases the efficiency of air conditioning and water heating. In warmer climates, especially in

[11] Note that if homes used gas for cooking, that was modeled as being true even after "electrification". Some homeowners may instead opt for full electrification including cooking to avoid fixed charges for gas service if they have the panel capacity for it. "Electrification" as used here also includes a fixed package of HVAC and WH equipment that upgrades efficiency in homes that are already electric. For a more detailed analysis of electrification across a full ResStock sample, see (Present, 2022)

homes with electric heaters, the electrification package reduces electric loads. However, in colder climates, the switch from heating with gas or fuel oil leads to an increase in home electric loads.

The net effect of both envelope upgrades and electrification is usually an increase in electricity consumption due to the increase in electric heating loads. However, the energy reductions from the envelope package are higher when combined with electrification. That is, an equal percent decrease in electricity load from the envelope upgrade leads to a higher total reduction when combined with an electrification package that increases home electricity use. This suggests that there are positive synergies between efficiency upgrades and electrification in terms of electricity use.

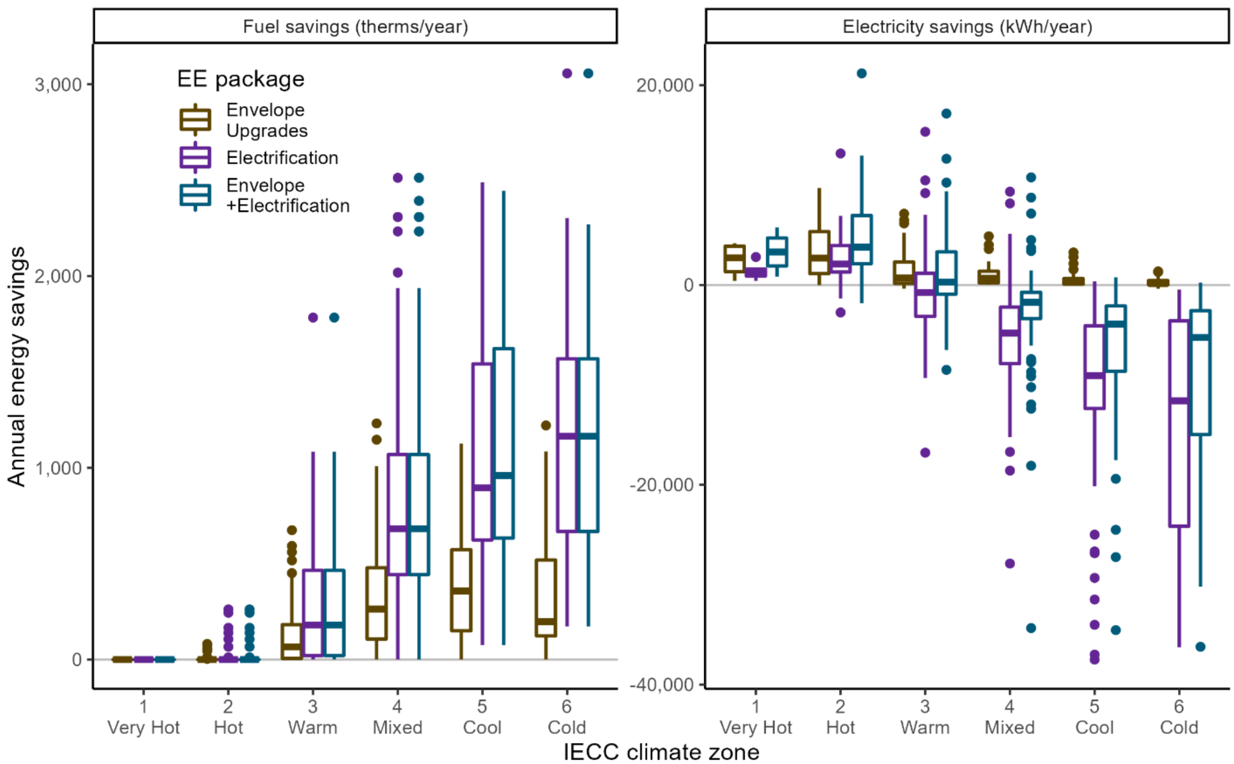

Figure 10. Annual energy use reduction for each upgrade package, by IECC climate zone

Figure 11 displays the annual fuel, electricity, and total bill savings for each upgrade package. The envelope upgrade provides bill savings for electricity and gas by reducing the energy needed to heat and cool the home. The electrification upgrade reduces fuel bills and usually increases electric bills. In general, the fuel bill savings exceed the increase in electricity cost increase, leading to a net savings in most homes. For each individual building, this depends primarily on the local electricity rate, fuel rates, heating setpoint, climate zone, and baseline equipment type. When combining envelope and electrification upgrades, the net energy bill is reduced in more than 75% of homes.

The combined average bill savings from envelope and electrification upgrades ($478/year) is less than the sum of the average savings from the envelope ($460/year) and electrification ($43/year) upgrades individually. This implies that the value of either upgrade is lower if the other upgrade is already adopted. For example, an envelope upgrade leads to higher savings in a home with inefficient HVAC equipment compared to a home with efficient equipment.

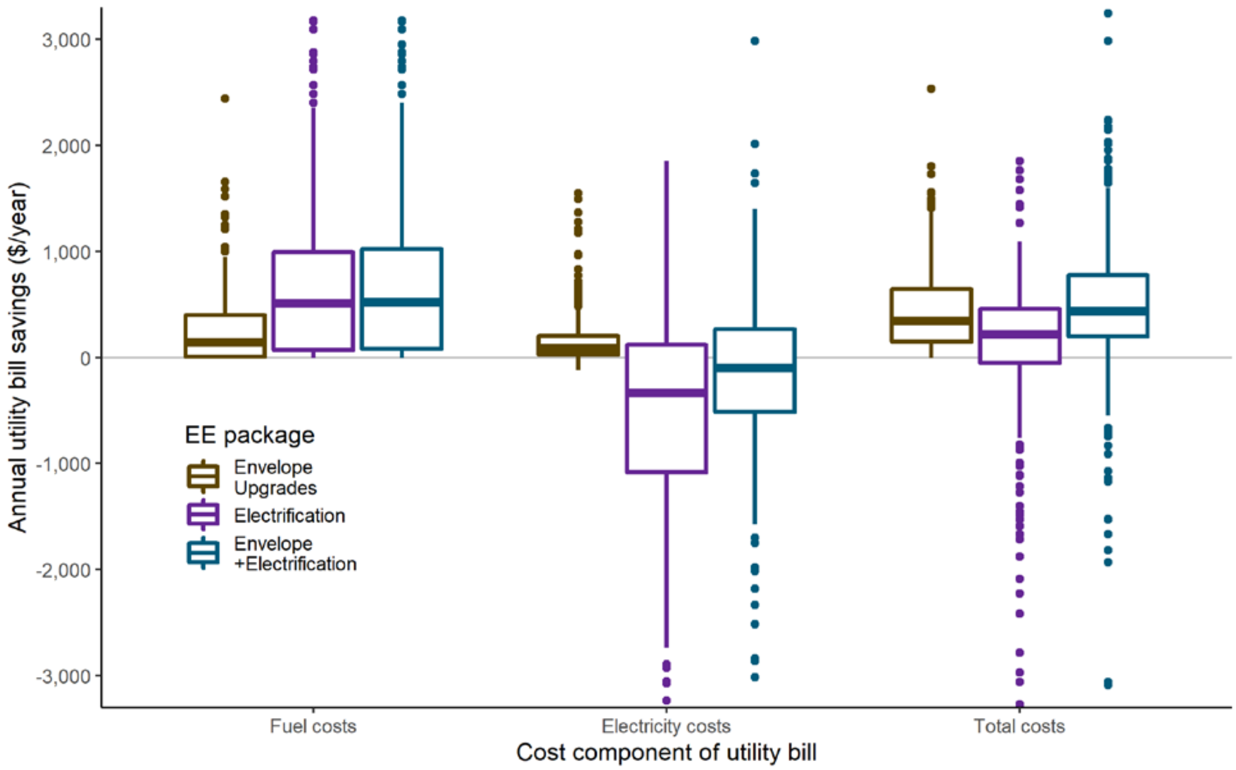

Figure 11. Annual bill savings by upgrade

Heating fuel plays an important role in determining savings from an upgrade package, as shown in Figure 12. The electrification package results in bill savings for all homes modeled that use fuel oil but leads to bill increases for a significant number of homes using natural gas. Bill savings from the envelope upgrades are also highest for buildings using fuel oil. These results are due to fuel oil being more expensive than natural gas. Additionally, the electrification package increases bill savings for all buildings that already use electric heating because the upgrade increases the efficiency of electric HVAC and water heating equipment, with less benefit in colder climates due to the decreased efficiency of the equipment at lower temperatures.

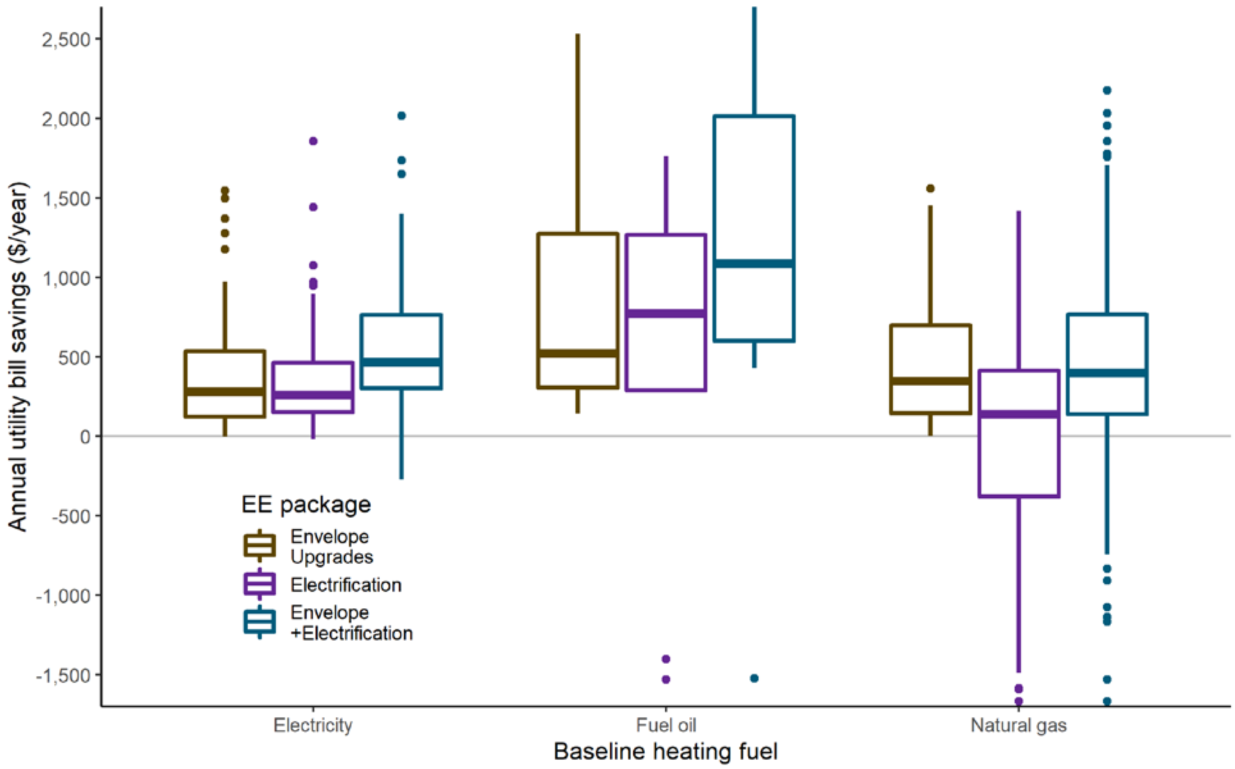

Figure 12. Annual utility bill savings by upgrade and baseline heating fuel

Annual bill savings must be weighed against upgrade costs. In the case of retrofits, this depends on both the cost of the upgrade and the difference in future replacement costs of the upgrade and the original system. For an upgrade to make economic sense, the annual utility bill savings must be sufficient to offset the present value of these costs. While the analysis workflow can run these calculations (in REopt), we do not report net present value results for EE upgrades because of a lack of consistent data for their costs and lifetimes across different buildings and geographies.

In addition to bill savings for the individual homes, mass adoption of efficiency and electrification can have an impact on the electricity grid. We calculate two metrics—annual wholesale electricity reduction and load reduction during grid peak—to measure the impact of a home retrofit or DER package on the grid.

Figure 13 displays the annual wholesale electricity cost reduction for each upgrade package by climate region. As expected, the envelope upgrade reduces wholesale electricity costs. For warmer climates regions, the prevalence of electrified buildings leads to wholesale electricity cost reductions from the higher-efficiency equipment in the electrification package. The electrification of homes in colder climates, on the other hand, results in higher electric use and therefore higher wholesale electricity costs. However, the envelope upgrade combined with the electrification upgrade significantly reduces the wholesale electricity cost compared to electrification alone.

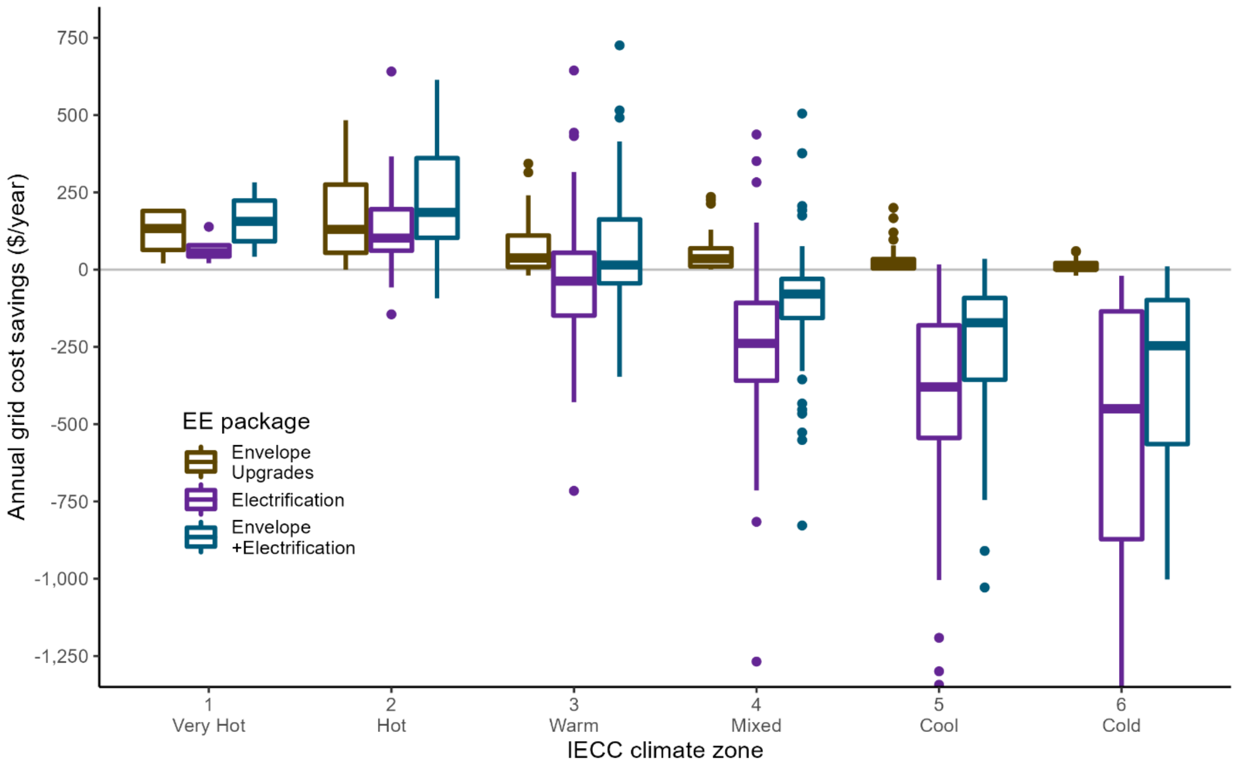

Figure 13. Marginal wholesale electricity cost reduction by upgrade package and climate zone. Based on Cambium 2021 data

Figure 14 shows the effect of EE upgrades on load during peak hours. Similar to wholesale electricity cost savings, the envelope upgrades result in a reduction in peak load. However, the electrification package also reduces peak loads across all climate zones. The electrification package replaces the existing air conditioner unit (if it exists) with a more efficient ASHP. This leads to a reduction in electric loads in the summer months when peak loads typically occur. Continued electrification and increased adoption of solar PV, which has a higher production factor in the summer than in the winter, may result in a shift in peak load from summer to winter (Mai et al., 2018). In this case, the electrification package could increase peak load instead of reducing it.

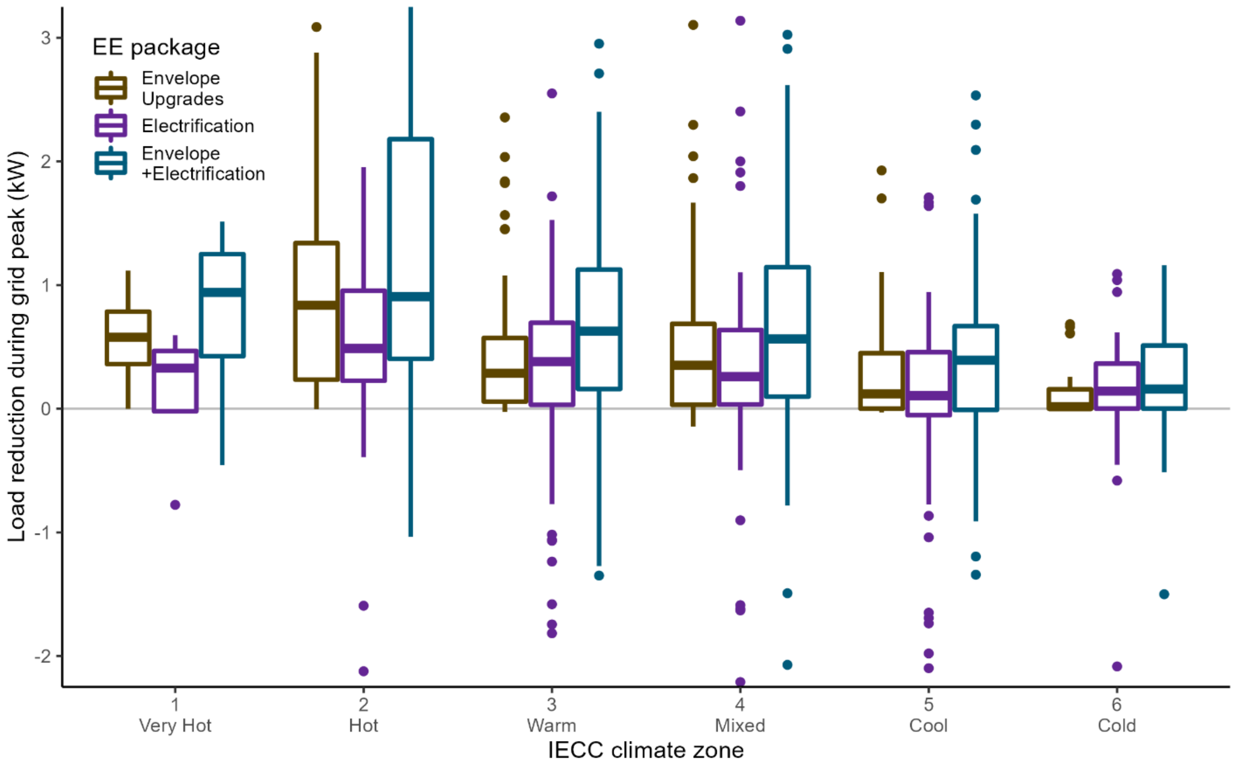

Figure 14. Home load reduction during grid peak from EE upgrades by climate zone

Figure 15 shows the emissions reduction from each EE upgrade. The envelope upgrade reduces emissions, but the electrification upgrade can increase total emissions for some houses. Implementing both envelope and electrification upgrades further reduces emissions compared to either upgrade individually. However, the combined average emissions reduction of 3.24 tons CO_2e/year is less than the sum of the average reduction for the envelope (2.02 tons CO_2e/year) and electrification (2.15 tons CO_2e/year) packages individually. We note that electricity emissions are levelized over a 25-year period and account for future renewable energy deployments; however, the levelized emissions rate could change if the rate of renewable energy adoption is faster or slower than anticipated.

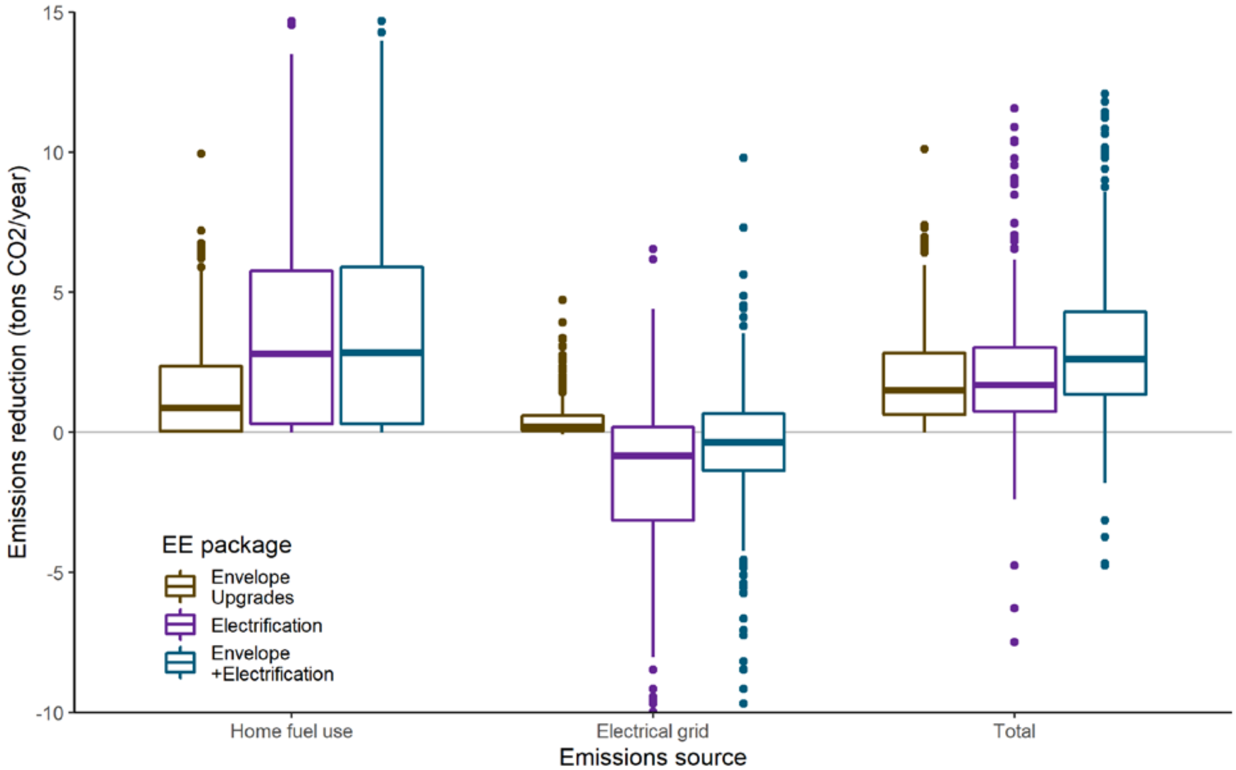

Figure 15. Emissions reduction from EE upgrades Emissions calculated using 2021 Cambium LRMER.

3.3 DER System Sizing

We assessed the value of residential PV and batteries using the same analysis framework as for the EE upgrades. The workflow determines the optimal size of PV and battery systems for each home based on the cost functions described in Table 3. In some cases, the capital cost of the DER outweighs the economic benefits, and the DER is not adopted. The results below show the results for where it would be cost effective to install[12] PV and/or battery systems across the five DER optimization scenarios. In the following section, we compare the value of EE and DER upgrades using the proposed metrics.

Figure 17 shows the locations of homes with cost-effective DERs and the electricity rates used for each county in the United States. Cost-effective PV systems are scattered around the United States, while cost-effective batteries are mostly in areas with time of use or critical peak pricing rates where there is a large difference between on peak and off peak costs, such as parts of New

[12] Actual adoption depends on many factors, including local shading, customer preferences for efficiency/resiliency, the availability of installers, and other factors.

York.[13] Note that the cost-effectiveness calculation does not consider the value of resilience, emissions reduction, or grid benefits, and assumes that net metering is allowed.[14] The battery systems, which do get sized, provide an average of three to five hours of backup power during grid outages. The resilience benefits this provides depends on the frequency of power outages and the cost of a loss of power.

PV value is driven by the combination of utility rate and solar capacity factors. PV can be optimally sized in locations with low utility rates if they receive sufficient sunshine and can be optimal in locations with low-capacity factors if the utility rate is sufficiently high.[15] The economics of battery storage depend on arbitraging across rates in different time periods. Even with the substantial reduction in battery costs in the last decade, batteries are generally not cost-effective in homes, in part because most default residential rates do not vary based on time of use. The adoption of residential battery storage may be driven more by factors such as customer desire for resilience during power outages, or resource adequacy during grid peak periods.

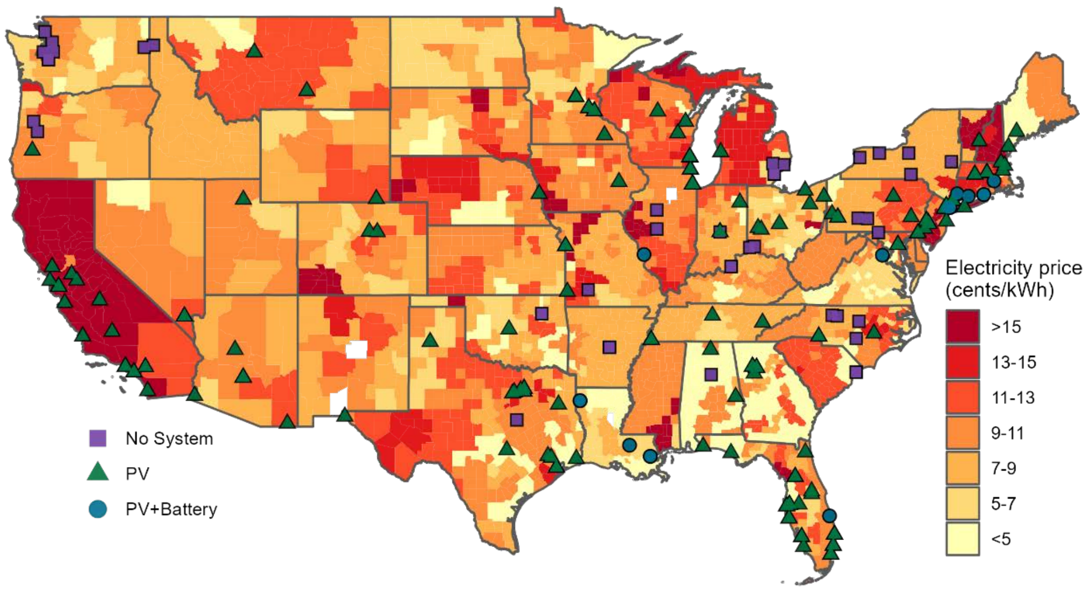

Figure 16. Location of homes with cost-effective DERs, overlaid with electricity price by county

Figure 17 shows the cost-effectiveness rate and size distribution of PV and batteries across the DER scenarios. PV is cost-effective in over 80% of homes, while batteries are only cost-effective in 10–25% of homes. Reducing DER costs and incorporating emissions leads to higher rates of

[13] Some caution must be used when interpreting the regions with battery installed given the challenge of linking residential utility rates to counties at scale. Subsequent analysis of the utility rates used found that the nearly all utility rates were correctly identified, but there were a small number of errors of either misidentified or corrupted rates. For example, a battery was sized in several Louisiana sampled homes due to a mischaracterized utility rate, which had high critical peak pricing. At the same time, there may be opportunities for battery systems that do not appear in the results given that the homeowner adopts an optional time of use or critical peak pricing rate.
[14] A scenario with no net metering was also run, however alternatives such as the recently adopted NEM 3.0 in CA were not included here. These two scenarios provide bounds on the potential benefits.

PV cost-effectiveness but does not impact the PV size distribution. Eliminating net metering lowers the cost-effective PV size but does not reduce the cost-effectiveness rate; removing net metering also increases the cost-effectiveness rate of batteries but reduces the battery size distribution. These effects occur because a lack of net metering provides an incentive for batteries to store excess generation from the PV rather than exporting to the grid; lower PV sizes for this scenario ensure that very little or no energy is exported to the grid.

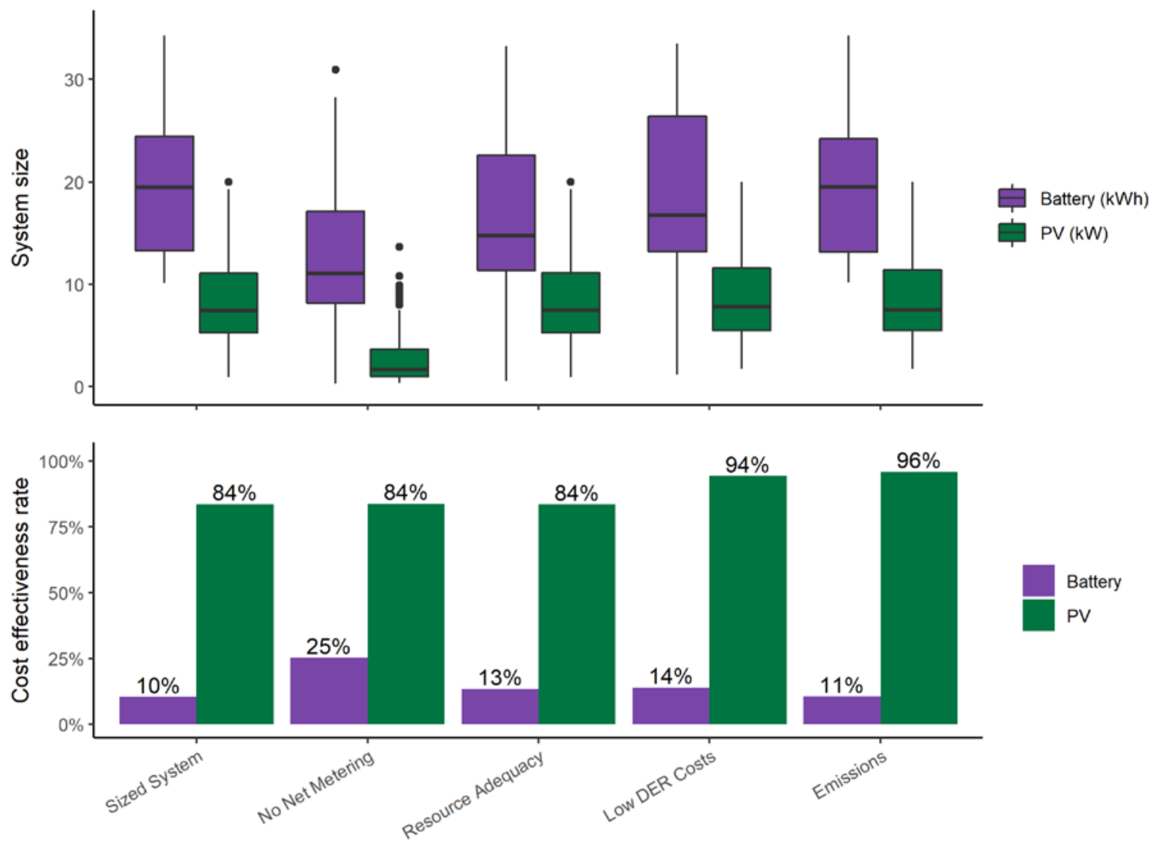

Figure 17. Cost-effectiveness rate of PV and battery across different scenarios

Figure 18 shows the relation between home loads, utility rates, and optimal PV size. PV is more likely to be sized in homes facing higher utility rates. The baseline building characteristics have a large influence on the optimal PV size, with optimal PV size scaling roughly linearly with energy consumption. Given roof sizing and utility policies in many locations, residential PV cannot be above a certain amount depending on the available roof area and building electricity consumption, so we included a maximum size limit of 20 kW for PV. It is worth noting that actual limits are often much lower due to roof area or utility-imposed constraints.

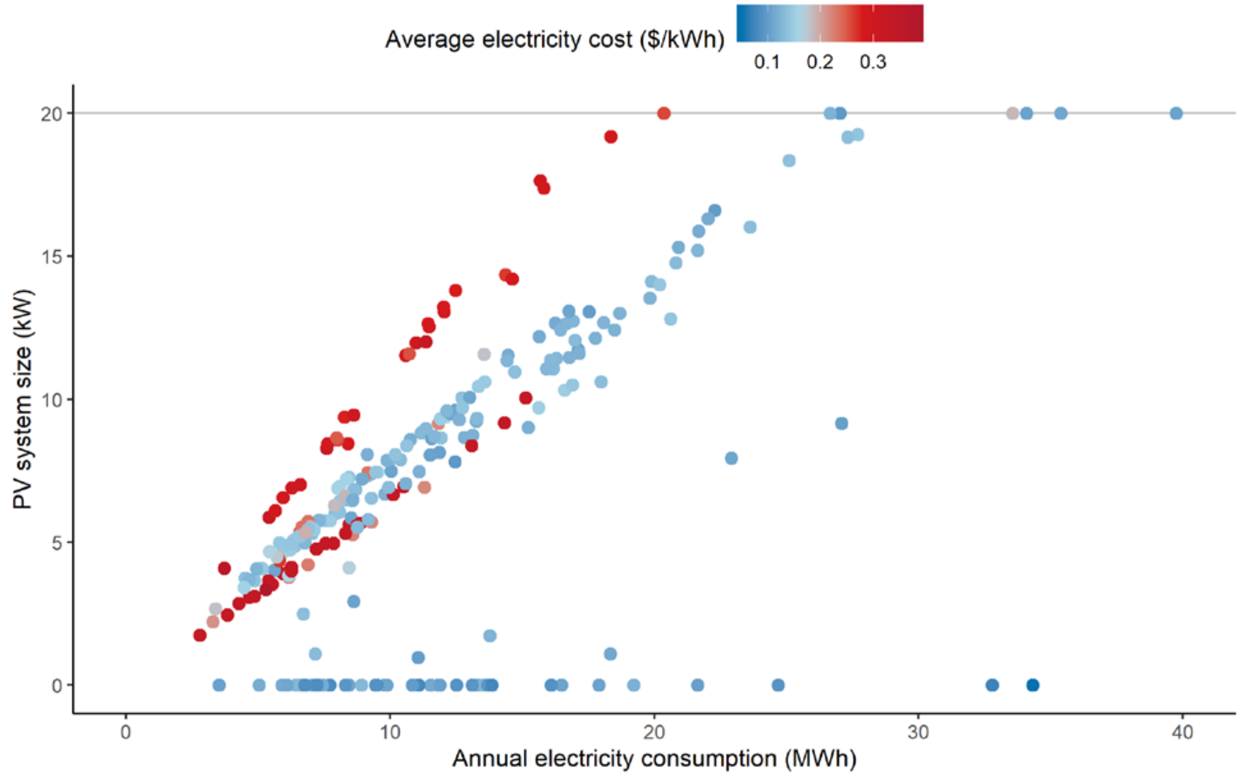

Figure 18. Cost-effective PV size for the sized system DER scenario in the baseline without EE upgrades

An important factor driving PV sizing are the net metering rules regarding PV export to the grid. Net metering policies allow customers to sell hourly excess electricity generated onsite from renewable energy sources back to utilities, offsetting electricity purchased from the utility (Smith et al., 2021). The compensation for exported PV ranges from zero payments, wholesale electricity rates, avoided utility costs, or retail electricity rates. Roughly two-thirds of states have retail net energy metering (Smith et al., 2021). While net metering customers can export to the grid in some hours, customers generally cannot be net energy producers on an annual basis. Total customer PV generation cannot exceed monthly or annual home loads depending on the specific utility rules. We model an upper end net metering scenario, with compensation at retail rates and PV generation limited by annual home load. We also model the other end of the spectrum under the No Net Metering scenario, with no compensation for exported PV.

PV scales with home load because of the net metering constraint that limits annual PV generation to not exceed annual home load. Thus, a higher annual home load relaxes the constraint and allows for more PV generation. Figure 19 displays the relation between PV capacity factor and PV size divided by average home load, with the gray line denoting the home net metering limit. There is a clear correlation between this limit and the PV that gets sized. Most buildings size a system slightly above the net metering limit to account for degradation of the PV system. Interestingly, for some homes with very high electric rates that vary by tiers, time of use, or weekday versus weekend, it is optimal to oversize the PV system and curtail during lower priced periods to be able to export more during higher priced periods. These high utility rates, which correspond to TOU rates, also lead to battery adoption and the outliers at the top of Figure 19, while outliers below the line are homes where the 20 kW limit affects PV sizes. However, not every utility may allow this in practice. Figure 19 also displays the result that buildings with *higher* PV capacity factors have relatively *smaller* PV systems installed; this is a consequence of the constraints on maximum PV generation based on building load.

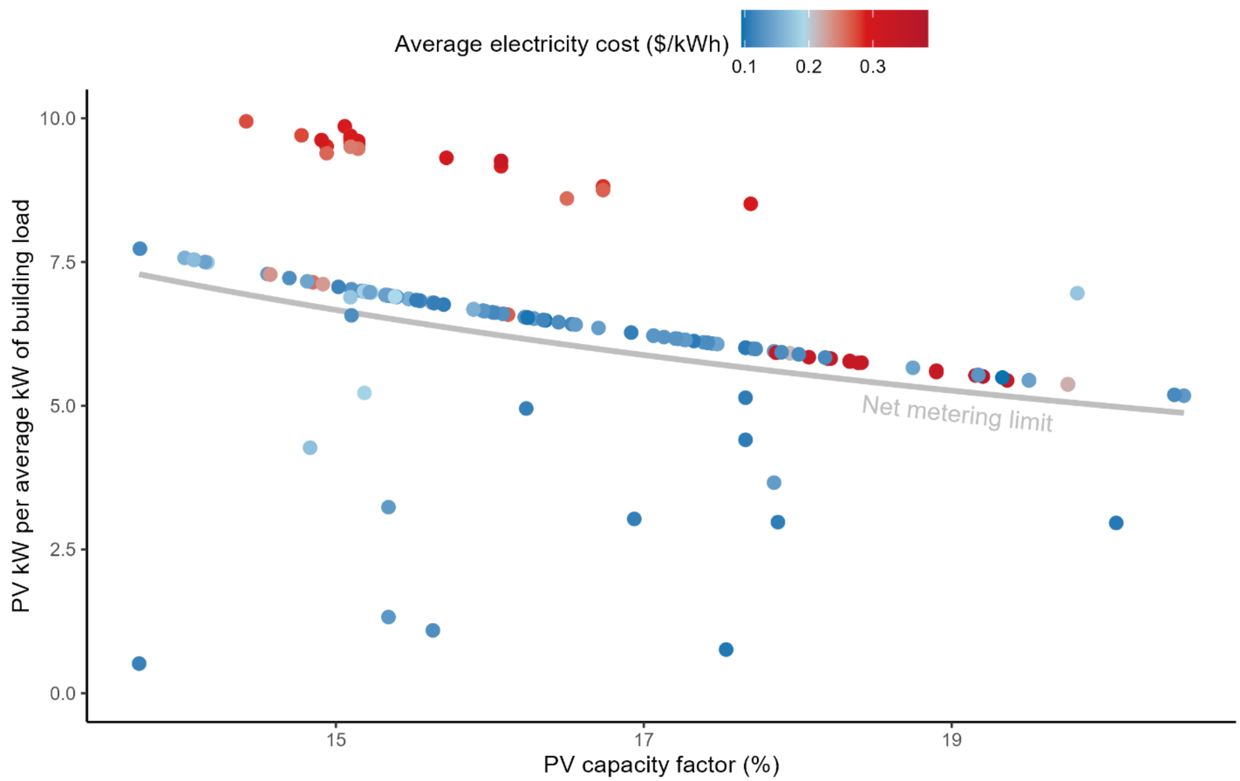

Figure 19. Relation between PV capacity factor and PV capacity normalized by average home load for the Sized System DER scenario Note scenarios where PV is not cost effective (so 0 kW are installed) are not shown here.

Figure 20 shows how PV sizing changes with building upgrades. The envelope package decreases the building electricity load, which results in a smaller PV system. Electrification increases building electrical loads, which leads to a larger PV system. The exception to this rule is for buildings that are already electrified, in which case the "electrification" upgrades act in a similar manner as the envelope upgrades to reduce PV size. Thus, building efficiency upgrades that reduce home loads have a negative impact on optimal PV sizes, and building electrification upgrades that increase home loads have a positive impact on optimal PV sizes.

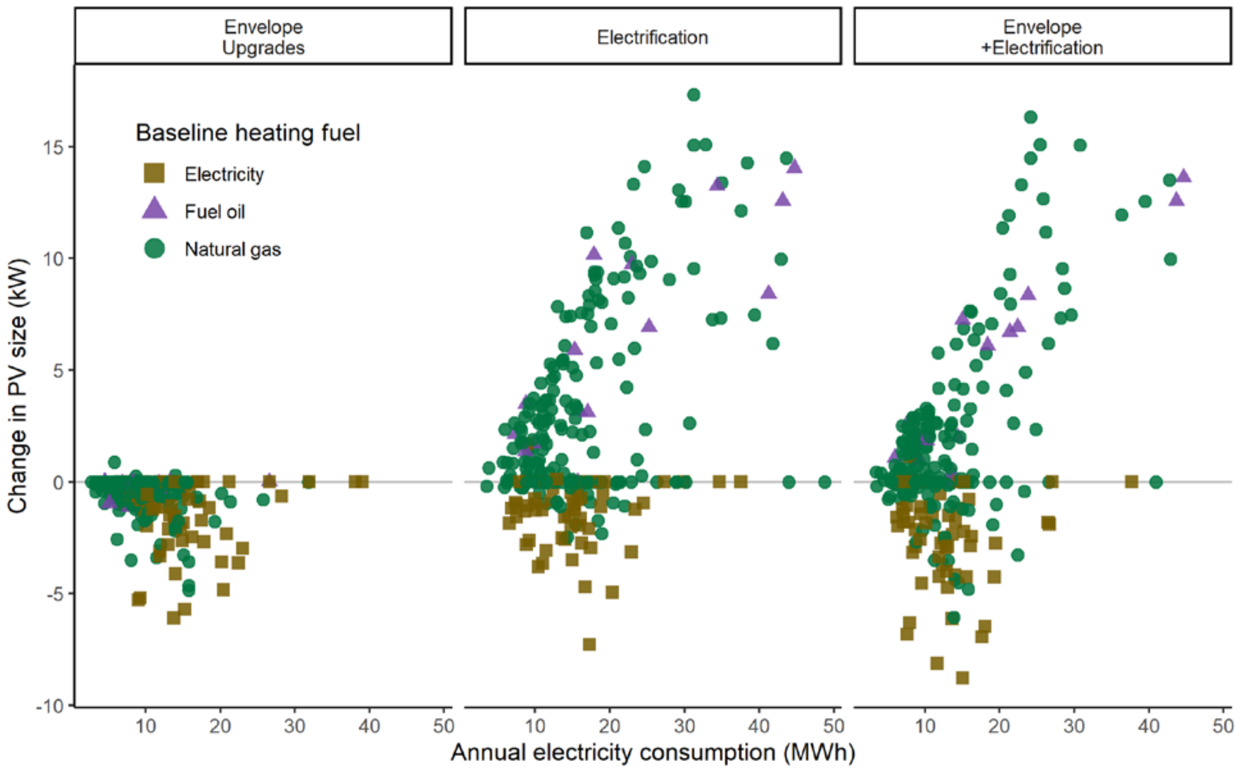

Figure 20. Change in sized PV system by EE upgrade and home baseline heating fuel for the Sized System DER scenario

3.4 Distributed Energy Resources and Efficiency/Electrification Combinations

The analysis framework allows EE and DER upgrades to be compared using the same set of metrics. The results discussed in this section show the value of EE and DER upgrade combinations using a variety of metrics. They also highlight the value of EE and DER upgrades separately, which enables analysis of how upgrade combinations interact and whether their combined value is additive.

Figure 21 shows the annual bill savings across scenarios with combinations of EE and DER upgrades. The combined value of the envelope package and DER upgrades is less than additive while the combined value of electrification and DER upgrades is more than additive. This is because the home load is dependent on the EE package and the PV size is dependent on the house load (see Figure 19). The electrification upgrade increases house load, which increases the average PV size, which then increases the value of the DER upgrade. We find that the total value of DER with electrification (for example, $827 for the Sized System case) is larger than the value of these two upgrades separately ($43 for EE and $663 for DERs); conversely, the total value of DER with envelope upgrades (for example, $1,049 for the Sized System case) is smaller than the value of the separate upgrades ($460 for EE and $663 for DERs).

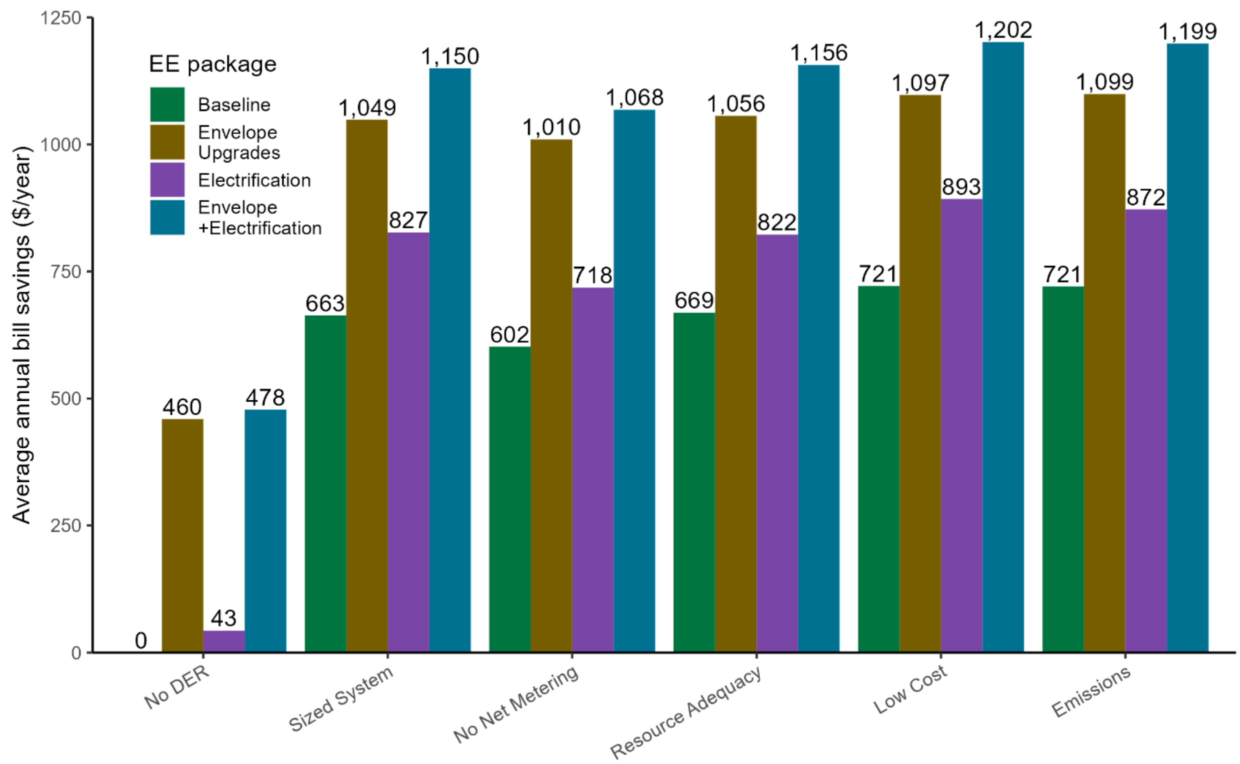

Figure 21. Average annual bill savings by scenario and EE upgrade.

Figure 22 displays the NPV of the DER upgrades by scenario and by EE upgrade. The values presented only account for the costs and benefits of the DER upgrade, so the efficiency upgrades only impact the home load. This also means that only homes where DERs were cost effective are included in the averages presented here. Figure 22 and Figure 17 can be used in tandem to determine the savings across the whole stock including homes where DERs were not installed. The building envelope package decreases the value of DER, while the electrification package increases the value of DER.

Not allowing for net metering has a clear negative impact on net present values by significantly decreasing the optimal PV size. The No Net Metering scenario leads to smaller system sizes and fewer homes where PV is cost effective, leading to the larger number of outliers. The outliers are also primarily homes that chose to install a battery along with PV so PV can be dispatched to meet building loads rather than exported. The Low Costs scenario leads to a substantial increase in NPV due to lower capital costs and also, therefore, a higher adoption rate of DERs. The Emissions scenario results in a decrease in NPV, and in some cases, negative NPV. This result is driven by an increase in system size and a higher adoption rate for DERs that would not be cost-effective without the emissions benefit.[16]

Including resource adequacy has a small effect on overall NPV of DERs, but it has a substantial effect for homes with a battery. PV does not provide resource adequacy credits. For homes

[16] Emissions are not considered in the NPV calculation for any of the scenarios.

without EE upgrades and with a battery, RA increases NPV by $742 on average. RA alone is not sufficient to incentivize battery storage, but can substantially increase cost-effectiveness when stacked with other value streams.

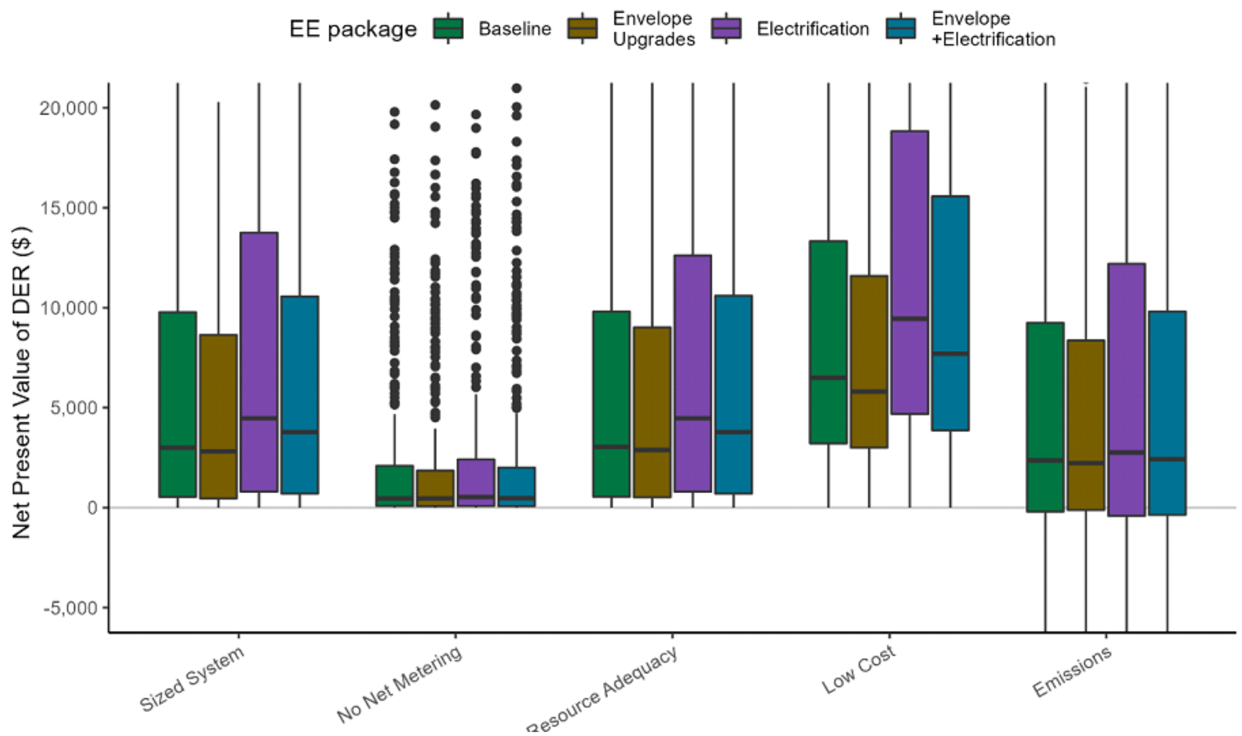

Figure 22. Average net present value of DER upgrades by scenario and EE upgrade

Figure 23 shows average wholesale electricity cost savings by scenario and EE upgrade. In scenarios with electrification upgrades and few or no DERs present, the total wholesale electricity cost can increase. However, electrification leads to cost savings in scenarios with large amounts of DER adoption. This is because the electrification enables larger PV systems to become cost-effective, with the increased loads leading more energy being used on site, larger PV systems being cost effective, and PV being cost effective for more households.. The increased sizes and number of households where PV is cost effective when doing electrification then outweigh the additional electricity use from electrification, leading to a net reduction in wholesale electricity costs.

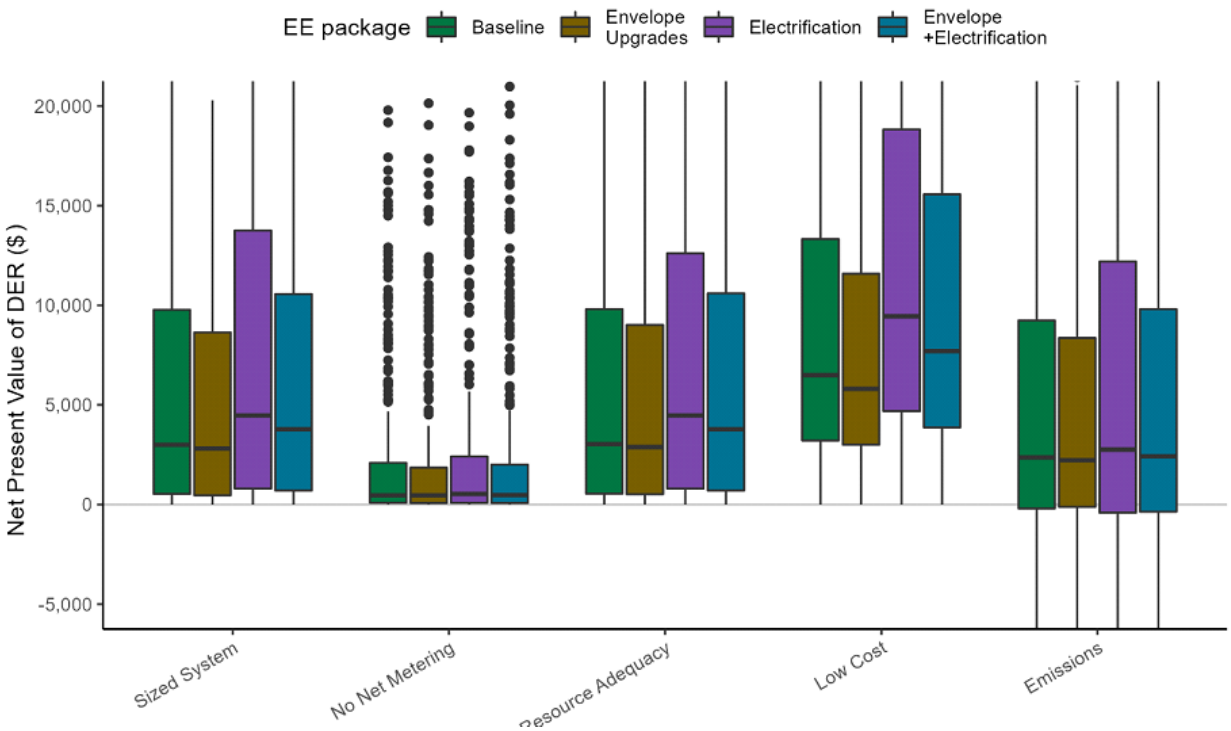

Figure 23. Average annual wholesale electricity savings by scenario and EE upgrade Cambium data is based on mid case scenario LRMER using 2021 data.

Figure 24 displays the reduction in home loads during the grid peak hour. Timing of PV generation is positively correlated with grid peaks, defined here as the 5% of times with the highest grid loads in Cambium, in most regions. This leads to large reductions in the home load during grid peaks when DER upgrades are added. The additional reduction in peak load under the resource adequacy scenario comes from batteries discharging at the grid peak to receive resource adequacy payments, while the additional reductions under the low costs and emissions scenarios largely come from additional PV added to homes. We note that the grid peak is based on modeled data for a U.S. grid in 2022; as more PV generation is added to the grid, peak times are likely to shift to evening hours, and the amount of peak load reduction from PV will likely decrease (Gates et al., 2021).

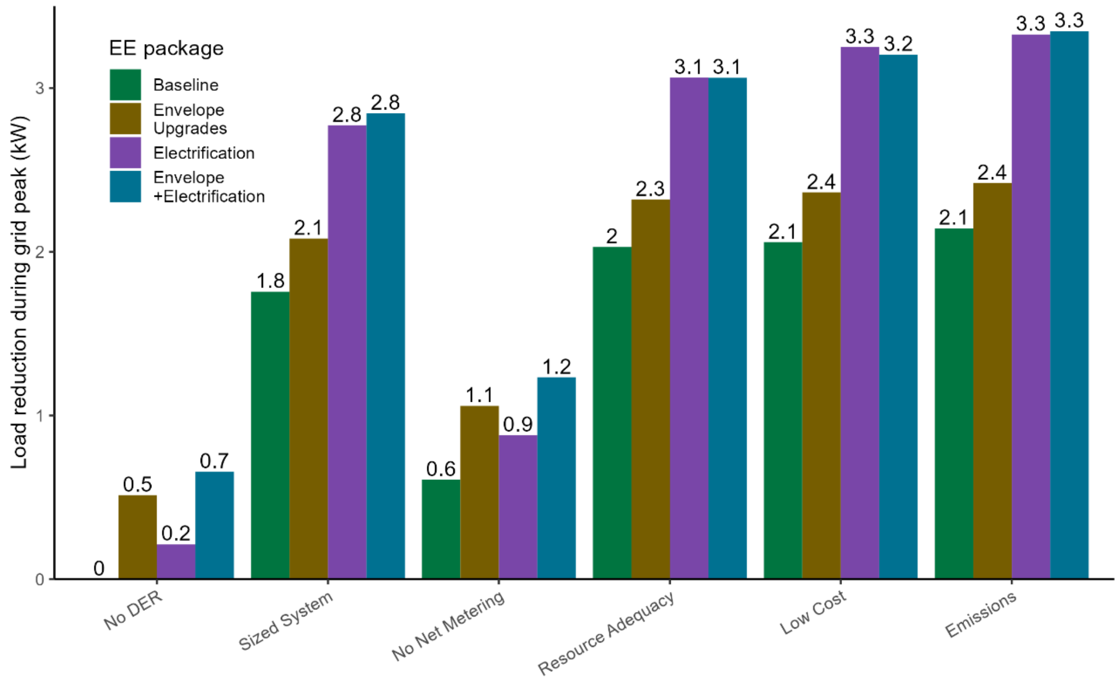

Figure 24. Average home load reduction during grid peak by scenario and EE upgrade

Figure 25 displays the annual emissions reduction by scenario and EE upgrade. To put these values into perspective, a typical passenger vehicle emits around 4 to 5 tons of CO_2e per year (EPA, 2018). Thus, a combined home retrofit and PV installation is roughly proportional to taking one car off the road. The addition of resource adequacy payments does not lead to emission reductions because it does not result in additional PV, and residential batteries have little impact on total emissions. One interesting result of note is that the results don't scale with the average system size. For example, the emissions reduction between sized systems and no net metering are not directly proportional to the difference in average PV array size. The two main drivers of this are that PV production is coincident with higher emissions rates on average and there are many more batteries in the no net metering case, which can time their discharge to match periods with higher emissions.

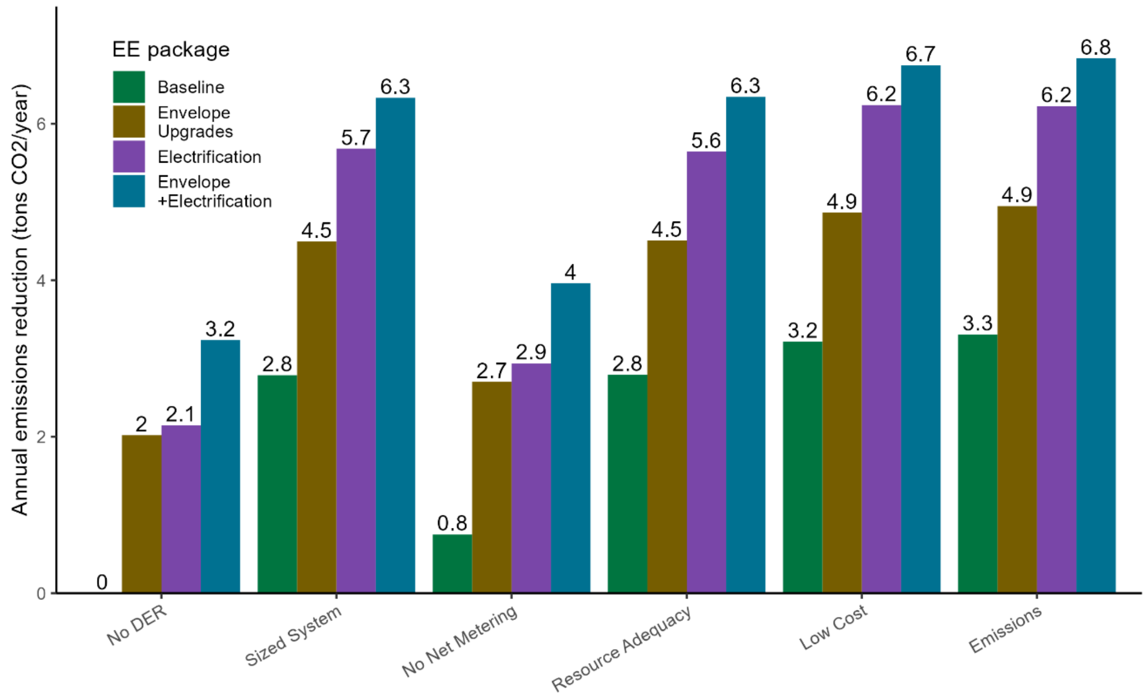

Figure 25. Average annual emissions reduction by scenario and EE upgrade

4 Conclusions

Changes to the residential building sector are set to play a key role in the broader transition toward renewable energy, with energy efficiency, electrification, solar, and storage, all providing different benefits for multiple stakeholders. The ability to provide quantifiable value to all stakeholders increases the attractiveness of EE and DER upgrades and can help stakeholders design programs and incentivizes to encourage adoption of these technologies. There is a need to understand the value and interactions between these various technologies in a consistent manner.

This work created and demonstrated a workflow that models the impact of residential EE and DER upgrades on homeowners, utilities, and society at a national scale. Our integration of ResStock, OCHRE, REopt, and relevant datasets into a single integrated workflow is well suited for answering questions related to the impact of residential energy upgrades on the energy sector. The national scale analysis presented in this report demonstrates the capabilities of the developed workflow and provides new insights into the economics and performance of residential energy upgrades. This work also evaluated the sensitivity of these results to multiple different potential futures, including scenarios where net metering is not present and where the value of resource adequacy and the social cost of emissions is captured in economic decisions.

Through our analysis, we found several results worth highlighting.

- The value of efficiency and electrification upgrades depends on the climate zone, the relative electricity and fuel costs and emissions rates, and the baseline heating fuel. Buildings using fuel oil tend to have the highest values of efficiency and electrification upgrades.

- Given our installed cost and utility rate assumptions, PV is cost-effective and battery systems are not cost-effective in most residential homes. PV adoption increases when installed costs are reduced or when emissions benefits can be monetized. Battery adoption increases when net metering is not allowed and when resource adequacy benefits can be monetized. Home envelope upgrades lead to lower optimal PV sizes, while electrification leads to larger optimal PV sizes.

- Combined energy efficiency and DER upgrades result in average emission reductions of 4.5–6.3 tons of CO_2e per year, roughly equivalent to taking a car off the road.

- While electrification upgrades on their own tend to increase the associated wholesale electricity costs, they reduce wholesale electricity costs when coupled with DER upgrades. This is because electrification enables larger PV systems to become cost-effective. Added benefits of more PV outweigh the additional electricity use from electrification, leading to a net reduction in wholesale electricity costs.

- Electrification reduces home loads during grid peak hours because heat pumps replace less efficient air conditioners that often contribute to the summer peak. However, this finding is dependent on the local climate and may not hold for locations that shift grid peaks from summer to winter months.

- We find small negative interactions between building envelope upgrades and electrification, suggesting that these upgrades provide slightly less value when they are combined.

While this work was able to answer several important questions, its potentially larger contribution is the development of a workflow and analysis framework that can evaluate the benefits of and interactions between EE and DER upgrades. The integration of residential energy modeling and optimization tools into an integrated framework allows users to calculate metrics that capture the full value of these upgrades. This framework can be used to inform the design of programs and incentives for EE and DER adoption for targeted customers at various geographic scales.

Our work can be expanded in several directions. Future work can model a larger number of buildings to provide a more complete coverage of the building and geographic diversity across the United States. Future research could also expand the approach to model the multifamily building sector, which was not examined in this study but makes up a large fraction of the total residential building stock. Multifamily housing is also critical for understanding the equity and social impacts of EE and DER upgrades given the tendency for lower income residents to live in multifamily housing. The framework can also evaluate controlled electric vehicle charging along with shifting HVAC and water heating loads, which could be significant sources of load flexibility in the future. Additional sensitivities, including different Cambium emissions scenarios, could also be included in future projects. Finally, this workflow can be coupled with economic and policy analysis tools to evaluate a policy's impact on EE and DER technology adoption and the benefits to homeowners, grid operators, and society writ large.

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Appendix A. Calculating Avoided CO_2-Equivalent Emissions

Cambium's long-run marginal emissions rates (LRMERs) "incorporate both the projected changes to the electric grid and the potential for an incremental change in electrical demand to influence the structural evolution of the grid" (https://data.nrel.gov/submissions/183). LRMERs are intended to be used when quantifying the emissions impact of a long-term change in electricity demand, such as the residential EE and DER packages analyzed in this study.

The levelized LRMERs used in this study are month-hour averages of CO_2-equialent emissions cast to an 8,760-length vector for each state in the continental United States, using the assumptions defined in Table 4.

Table A-1. Inputs used to calculate general levelized long-run marginal emissions rates used in this study, using the Cambium 2021 levelization workbook (https://data.nrel.gov/submissions/183).

User Inputs	
Emission	CO_2e
Emission stage	Combined
Start year	2022
Evaluation period (years)	25
Discount rate (real)	0
Scenario	Mid-Case
Global warming potentials	100-year (AR5)
Location	End-use
2050 fraction	0.00